SECOND
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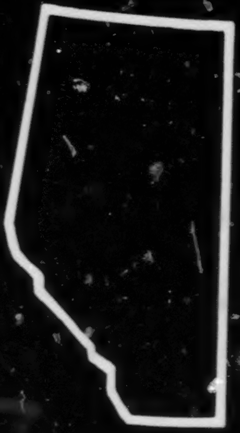

ACID FORMING EMISSIONS IN ALBERTA AND THEIR ECOLOGICAL EFFECTS

at the
PALLISER HOTEL
CALGARY, ALBERTA
MAY 12 - 15, 1986

Co-sponsored by Alberta Department of the Environment,
Canadian Petroleum Association, Energy Resources Conservation Board,
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ACID FORMING EMISSIONS IN ALBERTA AND THEIR ECOLOGICAL EFFECTS

Proceedings of the Second Symposium/Workshop

Held at

Calgary, Alberta
1986 May 12-15

Edited by

H.S. Sandhu
A.H. Legge
J.I. Pringle
S. Vance

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TABLE OF CONTENTS

Page

PREFACE v

PART 1: SESSION PAPERS . . . .

How's That Again? Explaining Science to Your Neighbour
James P. Lodge 1

Research/Uncertainty/Management: Ménage à Trois?
Robert A. Goldstein and James Davis 13

The Alberta Acid Deposition Research Program (ADRP) Overview and Status
R.L. Findlay and C. Primus 29

Acid Deposition: Research, Monitoring, and Management Strategy in Western and Northern Canada
R.G. Wilson and H.S. Sandhu 39

An Overview of Alberta Environment's Acid Deposition Program
H.P. Sims, G.A. Singleton, and H.S. Sandhu 55

Acid Deposition in the Western United States: An Assessment
P.M. Roth 79

The Role of Acid and Base Substance in Wet and Dry Deposition in Western Canada
P.W. Summers 85

An Inventory and Forecast of Acid-Forming Emissions in Alberta
D.G. Colley and D.J. Picard 117

Atmospheric Measurements, Monitoring, and Modelling of Acid-Forming Emissions in Alberta
E. Peake, R.P. Angle, and H.S. Sandhu 137

An Analysis of Numerical Models of Air Pollutant Exposure and Vegetation Response
S. Krupa, R.N. Kickert, and M. Nosal 163

Air Pollution Measurement and Effects Research: A Perspective on Agriculture and Forests
H.C. Jones, F.P. Weatherford, J.C. Noggle, and C. McDuffie, Jr. 189

Soils and Geology Sensitivity Mapping of Alberta and Western Canada
N. Holowaychuk, R.J. Fessenden, C. Palmer, and J.H. Weins . 209

Long-Term Observations on Soil, Plants, and Animals Adjacent to a Sour Gas Plant in Alberta
R.B. Church, K. Smith, and B. Ogilvie 243

Page

Variability in Forest Systems as it Relates to Elemental Sulphur Effects
D.G. Maynard and P.A. Addison 255

Air Pollution Measurements and Effects Research: A Perspective on Aquatic Damage
T.G. Brydges 287

An Assessment of the Potential Sensitivity of Alberta Lakes to Acid Deposition
P.K. Erickson and D.O. Trew 309

Microbiological Studies of Lakes Receiving Acid Deposition
S.S. Rao and B. Kent Burnison 337

Methodological Issues in Evaluating the Health Effects of Exposure to Acid-Forming Emissions
T.L. Guidotti and M.K.W. Cottle 359

Do Airborne Pollutants Affect Animal Health?
M.G. Prior and R.W. Coppock 391

Health Effects of Acid Deposition in Canada
B. Stern, M. Raizenne, R. Burnett, and C. Franklin 413

PART 2: PANEL STATEMENTS

Current Status and Future Direction of Environmental Regulation and Policy
A.D. Crerar 423
I.R. Smyth 428
M.J. Chorel 431
V. Millard 435

PART 3: SUMMARY REPORT ON THE WORKSHOP SESSIONS
B.R. Croft and E.R. Brushett 439

Acknowledgements 441
Introduction 442
CPANS/APCA Role 442
Workshop Agenda 443
Identification of Issues 444
  Communications 445
  Monitoring and Modelling 447
  Biological Effects 450
  Emission Control Technology 451
Recommendations for Future Research 452
  Communications 452
  Monitoring and Modelling 454
  Biological Concerns 457
  Emission Control Technology 459
Summary and General Recommendations 461

PART 4: LIST OF PARTICIPANTS 463

PREFACE

Over the past fifteen years a series of scientific symposia/workshops have been held to address the question of the environmental effects of air pollution on the environment in Alberta. A published proceedings resulted from each of these meetings. The first three of these meetings were referred to as the Alberta Sulphur Gas Research Workshops I, II, and III, were two days in length, and were held in 1973, 1975, and 1977, respectively. The objective of these workshops was to provide the forum for: (1) the presentation of research results on the environmental impact of sulphur gas emissions from industrial plants operating in Alberta, (2) the opportunity to exchange ideas among concerned parties in government, industry, the university, and the public, and (3) the identification of gaps in our knowledge.

By the late 1970s, however, the focus of the issue of air pollution and environmental impact in Alberta shifted from the environmental impact of sulphur gas emissions from industrial plants to the environmental impact of acid deposition resulting from oxides of sulphur and nitrogen.

This change in emphasis was a result of national and international concern about "acid rain." A fourth meeting was held in 1982 to address the question of acid deposition in Alberta. Both the format and title of this meeting were altered from the previous workshops to accommodate the expanding scope of the research activities and the need for increased communication among concerned parties in government, industry, the university, and the public. The meeting was called the First Symposium/Workshop on Acid Forming Emissions in Alberta and Their Ecological Effects, and was three days in duration. The symposium was two days long and provided the formal forum for the presentation and discussion of research reports, while the workshops lasted for one day and provided the opportunity for intensive discussions of the issues arising from the symposium and for the formulation of recommendations for future research.

As a result of increasing public and scientific concerns about issues of acid deposition in Alberta, a fifth meeting was held in May 1986, called the Second Symposium/Workshop on Acid Forming Emissions in Alberta and

Their Ecological Effects. For the previous four meetings, a call for papers was sent out and the meetings were structured around the papers submitted. For the fifth meeting, in addition to the call for papers, papers were invited by the Steering Committee. This allowed the Steering Committee to select only those papers which would meet the objectives of the meeting. Additionally, great effort was made to obtain public involvement both before and during the meeting. Each speaker was informed of the nature of the expected audience in advance and was requested to present the paper in a simple and clear manner.

The following were the objectives of the symposium and workshops:

Symposium

1. To provide perspective and awareness on the issue of acid deposition;
2. To improve the exchange of information on environmental research, monitoring, and control technologies and control policies; and
3. To involve the public and hear their concerns.

Workshops

1. To provide an opportunity for participants from all sectors (industry, government, the university, and the public) to express their ideas and concerns on the issue of acid deposition;
2. To identify and provide the rationale for future research needs; and
3. To provide a written summary of the workshop conclusions.

The Steering Committee gratefully acknowledges the help of the many people who contributed to make the Second Symposium/Workshop a success. We especially thank Mr. Carl L. Primus, Assistant Deputy Minister, Environmental Protection Services, Alberta Environment, for giving the opening remarks and welcoming the participants. We wish to thank the chairpersons for overseeing the sessions and the workshops. A special note of thanks goes to Mr. Brian Croft, Dome Petroleum Company Limited, representing the Canadian Prairie and Northern Section (CPANS) of the Air Pollution Control Association for organizing the workshops and providing the summary of those workshops.

We also express our appreciation to the staff from the Kananaskis Centre for Environmental Research, the University of Calgary, the Research Management Division, Alberta Environment, and students from the Faculty of Science and Technology, Mount Royal College for their assistance in making the Second Symposium/Workshop a success. Special thanks are due to Ms. Meliza Canafranca for typing the entire proceedings.

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PART 1: SESSION PAPERS

HOW'S THAT AGAIN? EXPLAINING SCIENCE TO YOUR NEIGHBOUR

by

James P. Lodge[1]

ABSTRACT

In a world in which all people are neighbours, the scientist carries a dual responsibility when he talks about science. The first of these is to attempt, whenever an opportunity is presented, to communicate the facts of science appropriate to the situation to his neighbours. The second is to make it as clear as possible where the facts end and opinion begins.

This situation will be explored, in not too serious a vein, in the context of the scientific disciplines related to acid rain.

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[1] Consultant in Atmospheric Chemistry, 385 Broadway, Boulder, CO 80303

1. INTRODUCTION

There is a very old story about a very slightly educated plumber who wrote a letter to the chemistry department at the state university. It said, "Dear Sir, I have discovered that muriatic acid cleans out pipes pretty good. Is there any reason I shouldn't use it?" The letter was passed around and finally landed on the desk of a very young professor. He wrote back, "Employment of muriatic acid, or, more properly, hydrochloric acid, for the stated purpose will, with high probability, convert the metallic elements in the pipes into chloride salts." He almost immediately got a letter back from the plumber, "Thanks for the information. It sure is good for cleaning out pipes." The young professor wrote back, "Employment of muriatic acid will cause chemical changes that are detrimental to the cohesive properties of the alloys commonly employed in pipes." He got a letter back once again, "Glad you agree. It sure seems a good way to clean the pipes." At this point, the young professor realized he was failing to communicate, and passed the letter to a very elderly colleague. The colleague wrote, "Don't use muriatic acid to clean pipes. It eats the hell out of them." In due time a letter came back, "Why the hell didn't you say so in the first place?"

Much closer to home, both in time and space, an old friend of mine wrote a book, supposedly for high school students, on meteorology. I am not sure where my copy has gotten to, so I will have to try to give the flavour of the book without actual quotation. In essence, it said something like, "We all live in air. Air contains oxygen and nitrogen. Air also contains water vapor. When the air contains too much water vapor, it forms clouds. Clouds sometimes are involved in storms. Storms are caused by advection of vorticity."

These stories are both examples of one of the major failings of specialists of all sorts--not just scientists. It is easy to get so immersed in the jargon of our particular specialties that we simply fail to communicate to those outside those specialties. It seems inconceivable to a chemist that anyone should fail to understand the meaning of pK_a, fail immediately to picture a GC with an ECD, or instantly visualize the formula for 1-naphthol-6-sulphonic acid. With botanists, it is the Graeco-Latin names of plant parts, and Latin binomials; the *Avena* coleoptile test for auxin activity is certainly self-evident. For that matter, as one of my avocations, I spend a certain amount of time in the company of theologians who tend to believe that everyone certainly understands the meaning of the prolepsis of the Eschaton. Statisticians talk at great length about normality, meaning by it something absolutely different from what the chemists, physicians, psychologists, etc., do, and then deliver the final blow with talk about heteroscedasticity.

The ultimate comes when one tries to associate with physicians. Once, a number of years ago, I sat in on a bull session of meteorologists, convened mostly to sympathize with a colleague who had just gotten into a great deal of trouble over a busted forecast. Finally, I remarked that forecasters were, after all, in much the same business as physicians, but somehow the physicians had arranged things so they could bury their mistakes. One old weather forecaster suddently got a gleam in his eye and said, "Yes, if they would only let us make our forecasts in Latin!"

One can go on endlessly satirizing, but the truth is that every profession, every specialty, every sub-specialty, every trade, every hobby, every family, and every location has its own special language. After all, if I tell you that my office is located just south of Broadway and Baseline, this information is quite incomprehensible unless I also tell you, or you already know, that it is in Boulder, Colorado. In a recent episode of the popular television show "Murder, She Wrote," one of the characters sported a marvelous 'Down East' accent. He was unmasked as an imposter, however, when it turned out that the people who had carefully drilled him in the accent had not taught him the meaning of 'Down East'.

To generalize all this, our species is a naming animal. Faced with any new situation, we go right back to our forefather Adam (Gen. 2:19-20) and start naming everything in sight, living, dead, mineral, or conceptual. What is completely omitted from the Genesis Creation story, probably because it was taken for granted, is that Adam did not make much sense to Eve until he had taught her the names he had given to the surroundings. Only then could they communicate, and of course they immediately got into trouble.

2. COMMUNICATION

In the preparation of this presentation, I spent some time with dictionaries, looking up 'communicate', 'communication', and other related words. I failed to find anything I thought especially quotable, but all definitions agreed in certain concepts that are worthy of note. First, communication requires a minimum of two participants. Second, they are both indeed participants: one does not communicate by drilling a hold in someone's head and pouring in data that are passively received. Third, what is exchanged between communicating people is, in both the general and the technical sense, information.

Now, one of the basic principles of information theory is that information is encoded. As Korzybski phrased it, the label is not the object, the map is not the territory. If we do not agree on labels, we have difficulty in communicating, and the probabilities are high that, if the condition persists, one or both of us will pass from frustration to anger. If you doubt this, consider the consequences, for example, of the historic inability of Christians and Jews to agree on whether the New Testament merits the label 'Scripture' or the argument between Christians and Moslems over the same designation for the *Quran*.

The consequences can be equally momentous if the two or more participants in communication believe that they are in fact applying a common label, when they are not. This is also, of course, the basis for a great deal of humour; an immediate instance is the young chemist and the plumber in my opening story. Another is a tale that surfaces periodically of an American couple who contacted an agent in Britain about the possibility of renting vacation quarters in the English hinterland. The agent wrote back, asking more details as to what they had in mind and, among other things, asked if they had any particular desires concerning the W.C. The Americans, according to the story, had no idea what this was, but finally convinced themselves that it meant 'Wayside Chapel'. Accordingly, they wrote a long description of their desires for comfort, remoteness, etc., altogether comprising several hundred words of double entendre that I certainly cannot reproduce in full. I leave it as an exercise for your imagination.

In fact, the nature of the English language is such that one can get a great deal of humorous mileage out of misunderstanding, not to say misdirection. There are many little classics of this. For example, think for a minute about the following: "Time flies. You cannot. They pass too quickly." Then again, there are statements that simply remain ambiguous, such as, "Two maggots were fighting in dead earnest."

In a sense, these ambiguities are part of the glory of the English language. Generally, one of the goals of those who concoct artificial languages is a decrease in ambiguity and it carries a price: it makes humour difficult and poetry impossible. I have actually read verse concocted out of Esperanto and it is dreadful.

However, if our aim in communication is to impart to another our knowledge of a scientific subject, then we have to fight against the ambiguity of the language, and we also have to establish a common encoding of the necessary concepts.

3. THE NECESSARY CONCEPTS

But here's the rub. What are the *necessary* concepts? I think all of us are familiar with the story of the school boy assigned to write a book review of a book about elephants. He began his review, "This book told me more than I ever wanted to know about elephants." A more worked-out example occurs in a science fiction novel of a number of years ago called *Gunner Cade* written by a pair of authors who published jointly under the pseudonym 'Cyril Judd'. According to the story, after a horribly destructive third or fourth world war, it had been concluded that some wars were inevitable but that they could be controlled by highly ritualizing the fighting. Gunner Cade was, as his name indicates, a soldier. However, in order for him to fight, he required some hours of preparation, spiritual, physical, and mental, together with an equal period at the end if he survived. Without the preparation he could not fight. He was then put into a situation in which the survival of several people depended on somebody shooting quickly. Furthermore, he could not be the somebody: the job had to be delegated and taught quickly. He made several attempts to describe the process of shooting a gun, beginning with what you did when you first got up in the morning. It actually took him a number of tries before he recognized that all that was really required was to point the gun and pull the trigger. He finally did so.

On a purely practical level, there are certainly available examples. The one that stands out in my memory occurred almost 20 years ago, when I spent a semester as a visiting professor at Louisiana State University, working closely with Professor Philip W. West. Generally speaking, one of the least favourite jobs among chemists (and, I suspect, most other disciplines) is the teaching of the single course in the subject intended for students with no plans to take any further courses--majors in home economics, agriculture, nursing, and the like. It is normally delegated to the most junior assistant professor who is afraid to refuse the job lest he lose his chances for tenure. However, Phil West absolutely loved to teach that course and his classes invariably got far better grades than those of any other teacher. Enrollment in 'Bonehead Chemistry' was large enough, however, to require a number of lecturers, and the balance of them were in fact very junior faculty, nearly all recruited from the major chemistry schools in California. The California schools, at that time, really believed and taught that the only important subject was theoretical physical chemistry, and that all of the other subdisciplines were simply special cases of that master subject.

Near the end of my stay, Phil left town for a week and, in his absence, the balance of the lecturers in the course met and selected the textbook for the following year. They left a copy on his desk with a note explaining that this was their selection. I was quite unaware of this.

The next Monday morning I arrived at the Chemistry Building just in time to hear a loud outburst of profanity from Phil's office. When I went in, he nearly threw the book at me. I got him calmed down enough to explain the situation to me. At his request, I thumbed through the book. Mind you, this was all the chemistry that these students were ever going to learn as far as the University was concerned. It had no discussion of the properties of elements or compounds. It did not contain a single chemical equation. It said absolutely nothing about industrial applications of chemistry or about cooking, fermentation, fertilizers, or anything of the sort. It sported numerous beautifully executed drawings of molecular orbitals and a lengthy discussion of the consequences of the Schroedinger equation.

In a brief, explosive visit to the office of the department chairman, Phil got the textbook changed.

4. SPECIFICS

It would be possible to go on telling the stories almost indefinitely but never coming close to the immediate subject of interest, which, in precise terms, should be called acid and acidifying deposition. Unfortunately, that precise phrase lacks both the zing and the brevity of 'acid rain'. However, the short phrase has spawned little more than mental pictures, in the lay public, of raindrops that smoke as they descend, like a Cecil DeMille conception of one of the Biblical plagues of Egypt. Virtually every cartoonist in the United States has already drawn his principal character standing in the rain holding an umbrella whose surface has mostly dissolved; that appears to plumb the limits of the humour anyone has so far been able to see in the entire affair, as well as largely exhausting the popular visualization of the subject.

Indeed, the popular view of environmental questions seems singularly humourless and hence very unforgiving. Not many years ago, I was involved in the controversy concerning how damaging the continued release of chlorofluorocarbons might be to the stratospheric ozone layer. One of the early advocates of the view that the damage would inevitably be extremely serious was Professor F. Sherwood Rowland; I was, for reasons that still appear valid, convinced that the actual impact would be far less. Toward the end of the period of real public awareness of the problem, a book appeared called The Ozone War by Harold Schiff and Lydia Dotto. One of the points that the book seemed at pains to make was that Rowland was a hero and Lodge a villain and that, even if it turned out that Rowland was totally wrong and Lodge totally right, Rowland would still be a hero and Lodge a villain. The logic involved was never explained; it was simply stated as an article of true faith.

One of the prerequisites for explaining science to one's lay neighbours is a clear understanding of what one is talking about. Recent developments have, in the present situation, tended to obscure rather than clarify this issue. For example, everybody knows that one of the major villains in the acid deposition story is sulphur dioxide. However, a great deal of the damage done by sulphur dioxide has no pertinence to its role as a precursor of sulphuric acid; it is, in its own right, quite toxic to plants and this toxicity does not appear to derive from its potential acidity but from its role as a potent reducing agent. Furthermore, on soils that are deficient in sulphur, sulphur dioxide can act as a potent fertilizer. For example, I have heard it said that, on the big island of Hawaii, if your papaya tree begins to grow old and to produce less fruit, you should pray to Pele for a volcanic eruption to dose the area with sulphur dioxide and rejuvenate the tree. It should also be noted that the sulphur dioxide removed by plants, either to their benefit or detriment, does not go on to become acid rain someplace farther downwind.

In a rather strange development, it has recently been declared that ozone is part of the acid deposition story and that ozone is an acidifying substance. Now, it is true that ozone appears to be part of the chain responsible for converting a certain amount of sulphur dioxide into sulphuric acid and/or sulphate. In that sense, some ozone is an acid precursor, though it would appear to be a rather small fraction of the total. What actually, however, appears to be the explanation is rather less creditable. Forests in some parts of Europe appear to be sustaining serious damage, to the point that it has been given the popular name of 'forest death'. The distribution of the phenomenon is such as to lead to a reasonable conclusion that pollutants are responsible. At this point, numerous prominent people, scientists and otherwise, leapt to a conclusion and gave it out publicly that the cause was acid rain. It was considerably after this that clear evidence came to light that lowered pH of precipitation was not at fault; the real cause was ozone. However, nobody asked the prominent people to eat their words. Ozone was simply redefined as part of acid precipitation. Important people were saved from embarrassment, but who can blame the members of the audience who take seriously the meaning of words for being confused?

Probably another source of problems derives from reporting the acidity (if any) of precipitation as pH. I do it myself. However, few people actually have a feeling for the nature of the logarithmic scale, including the chemists themselves. More than 50 years ago, there appeared a lengthy series of juvenile science-fiction books under the generic title of The Adventures of Tom Swift. The nominal author, Victor Appleton, was in fact a succession of a dozen or more writers. To avoid the appearance of design by a committee, certain style rules were enforced. One of these was that the verb "said," or any of its synonyms, never appeared without a modifying adverb. Perhaps 25 years ago, a group of jokes, based on this mannerism, began circulating that were called 'Tom Swifties'. One of them made the pages of Chemical and Engineering News. It was "'The pH is 3.5,' said Tom half-acidly."

Now, practically every chemist that I know immediately got the point of that joke, and most laughed. I told it to a large number that had not happened to see it when it was published. Not one of them objected in the slightest. Everybody perceived 3.5 as mid-way between a pH of 7, which is neutral, and a pH of 0, which all simplified treatment of the acid rain question characterizes as the lower limit of pH. Now, in the first place, there is nothing that limits pH to positive numbers. If ordinary commercial concentrated sulphuric acid was totally ionized (which it is not), it would have a pH of -1.56; it is a bit more than 36 N. In the second place, even if one assumes that a pH of 0 is, in some sense, the end of the line, it corresponds to a solution containing 1 mol L^{-1} of hydrogen ion. A truly neutral solution is not one that contains no hydrogen ion, but one that contains 10^{-7} mol L^{-1} hydrogen ion. However, this is a small enough quantity to treat as negligible, and the point mid-way between 1 molar and almost-zero molar is clearly 0.5 molar. The mid-point between these two figures is thus, effectively, 0.5 molar, corresponding to pH of 0.3, not 3.5.

By the same token, if the acidity of precipitation is totally caused by emitted sulphur dioxide, and if the relationship between source emission rate and ambient concentration is precisely linear, and if gross emissions of sulphur dioxide were cut in half, and if nothing else happened, the largest possible effect would be an increase in pH of 0.3. It would require a 90% reduction under these assumptions to change the pH a full unit.

Nothing is quite as easy as holding an opinion on a subject on which there are no data. When serious questions of the acidity of rainwater first arose, some 25 years ago, a lot of us took that to mean rainwater with a pH below 7. It was actually some time before anyone realized that the purest of water, in equilibrium with the atmospheric content of carbon dioxide, would display a pH of about 5.6. We suddenly had a new benchmark to which a large number of people still adhere. However, more recent studies have shown that the purest rains, collected in the most remote regions from the least contaminated air masses, display pH values in the range between 4.8 and 5.2, or thereabouts. Rains that deviate in either direction from that range are clearly more contaminated than those within it, on average. This is probably the pH of rain that would fall if all acidifying emissions were reduced to zero, once again on average.

I recently had occasion to examine a series of truly detailed analyses of precipitation samples collected in a rural community in central Minnesota. The average pH of the samples was in the vicinity of 5 or a bit over; I had no particular call to take an average. All samples certainly contained measurable quantities in both sulphate and nitrate. However, all also contained measurable quantities of formate, acetate, and other anions of low molecular weight organic acids. In fact, roughly three-quarters of the samples contained at least enough carboxylic acids completely to account for the measured pH, on the assumption that these were the sole companions of hydrogen ion in the samples. While it is undeniable that carboxylic acids can result from the partial oxidation of pollutant hydrocarbons released by human activity, they also arise prolifically from purely natural sources. These weak acids may be the primary reason for the depression of clean rainwater pH below that accounted for by carbon dioxide, and natural source variability undoubtedly accounts for some of the variation around the mean value.

I recently read a study of a small watershed in the Rocky Mountains, not far from where I live. The stream had a pH in the vicinity of 6. It was fed by precipitation with a pH of around 5. What made it noteworthy was the fact that the stream itself ran through a long stretch of peat bog with a soil pH of approximately 4, that pH, so far as can possibly be told, being maintained entirely by the acids produced by the peat.

To all appearances, that has been going on for millennia. However, when I spoke with the scientist who had supervised the study, I was told that the slightest increase in acid input into the system would undoubtedly lead to ecological catastrophe.

It appears that all lakes acidify, some cyclically, some terminally, depending on their geography, geology, and meteorology. Some of the sulphate and nitrate in the atmosphere is of natural origin. There is debate as to the true importance of nitrate in long-term acidification because of the activity of denitrifying bacteria which recycle sizable amounts of nitrogen compounds back into the atmosphere, predominantly as nitrogen, and to a much lesser degree as nitrous oxide. It is rarely considered that there are also de-sulphurizing bacteria busily at work converting oxidized sulphur compounds to hydrogen sulphide, dimethyl sulphide, and related gaseous materials that escape from the soil and from the waters. Some types of plants also have this ability.

It is difficult to cite facts of this sort without being accused of all sorts of things--disbelieving in the reality of acid deposition, toadying to the interests of industry, or sheer scientific incompetence. Nonetheless, I will plead not guilty to all charges. Unlike an attorney, who must make his client look good at all possible costs, a consultant cannot long survive without scientific integrity. Pleasing a given client at all costs does not provide a life income. I have told more than one prospective client that my opinion on his problem would be that he was at fault.

Clearly, there are areas in the United States and in the rest of the world where the combination of the wet and dry deposition of acid materials is far greater than can possibly be accounted for by natural processes. Strongly acidic rain, dew, and fog waters are certainly not beneficial to marble statuary, galvanized sheeting, or probably to many sorts of life forms that come in obligatory contact with them. In some geographical areas, the coincidence of a sizable number of bodies of water becoming acid, more or less simultaneously, could be too much of a coincidence to assign to the normal aging processes of bodies of water. What must, however, be stated simultaneously is that not all acid precipitation results from sources built by humans, not every lake that becomes acid is caused by acid precipitation, and not every tree that dies is caused by pollution. When we speak as scientists to enlighten our neighbours about the problems of the deposition of acid and acidifying substances, we need to do it with these complexities firmly in mind.

To lay a full discussion of the uncertainties in the process on our neighbours may tell them "more about acid rain than they ever wanted to know." On the other hand, to leave them with the impression that all is known, and it is simply a matter of making those dirty industries clean up all over the world, is to do them an equal disservice.

The Province of Alberta has a unique opportunity to assist in converting our present mixture of opinion and ignorance into fact, at least insofar as any problems within its own borders are concerned. You have here, what is in my opinion, one of the best-designed programs of the study of acid rain in the world. If it can be carried to its conclusion, you will know more about acid deposition in your own area than does any other jurisdiction. I can only hope that it will indeed be carried to its end, and that you will then tell your neighbours about it--clearly, unequivocally, and as comprehensively as their understanding allows and their patience permits.

RESEARCH/UNCERTAINTY/MANAGEMENT: MÉNAGE À TROIS?

by

Robert A. Goldstein[1] and James Davis[1]

ABSTRACT

Current environmental concerns of society are very complex and require sophisticated technical analysis for proper management decision-making. A new type of environmental research approach, the integrated approach, has recently evolved to provide necessary management tools. An example of this approach is the Integrated Lake-Watershed Acidification Study (ILWAS), which developed a general mechanistic theory of lake-watershed acidification. Key elements of the integrated approach are: (1) emphasis on mechanisms and processes; (2) quantification; (3) integration; (4) modelling; (5) long-term perspective; (6) interdisciplinary team effort; and (7) analysis of uncertainty.

[1] Environmental Assessment Department, Electric Power Research Institute, Palo Alto, CA

1. INTRODUCTION

Some years ago, one of us (R.A. Goldstein) became interested in the subject of ecological risk uncertainty analysis (Goldstein and Ricci 1981). At about this time, his wife was taking courses in commercial art and would discuss with him the concept of logos. These discussions stimulated him to develop a logo-picture that encapsulated the interaction between ecological research, management, and uncertainty (Figure 1).

The person in the figure represents the policy-decision maker or resource manager. The scales that she holds are to compare the consequences of alternative management strategies which include different components of research, pollution control, and effects mitigation. It is important to recognize that research, pollution control, and mitigation are not mutually exclusive, and that a given management strategy may contain elements of all three. The use of the scale to make comparisons emphasizes the need to quantify consequences; however, one must recognize that all consequences cannot simply be measured using a single metric, that is, dollars and cents. Value judgments vary among people. To some people, a loss of 10% of a fishery will be unacceptable, while others will be indifferent to a 50% reduction. Also, the same ecological effect can have different economic consequences to different segments of the population. A 5% reduction of a crop's yield can result in increased cost to the consumer but also increased income to the farmer.

Although we probably would all agree that justice should be blind, it is certainly not in society's best interest for the resource manager to be blind (Figure 1), especially when one considers that through her regulatory authority, she swings a very large and sharp sword. It is the responsibility of the technical community to supply the resource manager with data and models upon which to base her decisions and to clarify uncertainties inherent in these data and models. These uncertainties are represented in Figure 1 by the precarious state in which the manager is balanced on the data and models.

In the following paper, we will present some of our thoughts concerning ecological research, management, and uncertainty.

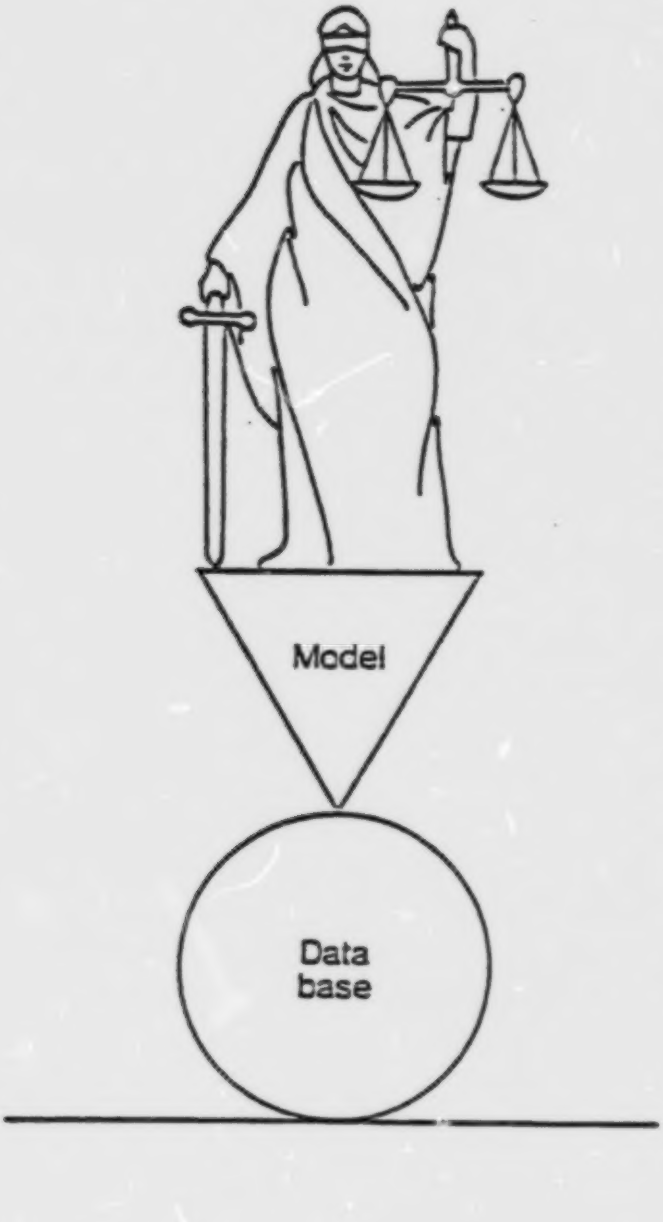
Model
Data base

Figure 1. Relationship between research manager, researcher, and uncertainty. (Refer to text for explanation.)

2. INTEGRATED ENVIRONMENTAL RESEARCH

Over the last decade, a new type of research approach has evolved to address the complex questions of environmental management and assessment indigenous to present-day society. This approach has been called the integrated approach (Goldstein and Legge 1986; Chen and Goldstein 1986). A prime example of this approach is the Integrated Lake-Watershed Acidification Study (ILWAS) (Goldstein et al. 1984) which will be used in the following discussion to illustrate the characteristics of the integrated ecological research approach.

The objective of the ILWAS was to develop a tool that could be used to assess the amount of surface water acidification that can or has occurred as a result of atmospheric deposition; that is, to develop a quantitative relationship between the acidity of deposition and that of surface waters. This was accomplished by developing a general mechanistic theory of lake-watershed acidification that takes into account the production and consumption of acidity by watershed biogeochemical and hydrologic processes, as well as atmospheric inputs of acidity. The original conceptualization of this theory was described by Chen et al. (1979) and Goldstein et al. (1980). The theory is formulated as a mathematical model that simulates, in an integrative manner, the multiple processes controlling lake acidity (Gherini et al. 1985).

The fundamental concept on which the design of ILWAS was based is that a lake's vulnerability to acidification can only be understood in the context of the biogeochemistry and hydrology of its entire catchment. Over a period of 4 years, the study carried out an intensive field and laboratory experimental program focused on three forested catchments in the Adirondack Park region of New York State. Although each catchment received about the same amount of precipitation of nearly identical quality, each had a lake with a different pH level and different pH dynamics. Of the three lakes, Woods was acid (typical outlet pH between 4.5 and 5.0), Panther neutral (typical outlet pH near 7), and Sagamore had more variable year-round pH dynamics, with an outlet pH typically between that of Woods and Panther.

Key characteristics of ILWAS, that are representative of the integrated approach, are: (i) emphasis on mechanisms and processes;

(2) quantification; (3) integration; (4) modelling; (5) long-term perspective; and (6) interdisciplinary team effort.

A mechanistic analysis, that explicitly includes the basic processes (such as canopy interception, canopy washoff, soil water flow, cation exchange, mineral weathering, nitrification, plant uptake of nutrients, in-lake sulphate reduction, etc.) that connect cause and effects, creates a framework for extrapolating results to other depositional and climatic regimes and other lake-watersheds. Empirical models, such as correlation relationships between watershed input and output fluxes, that treat the lake-watershed as a black box, cannot be rigorously extrapolated beyond the data base from which they are derived. Given the diversity of lake-watersheds, even within small geographical regions, the effort required to develop an empirical model that would be generally applicable is overwhelming. Although mechanistic analyses initially may appear to be more complex than empirical analyses, they are more likely to be the shortest route to general solutions.

As was pointed out in the discussion of Figure 1, the policy maker needs to quantitatively compare the consequences of different actions. It is not sufficient to answer the question, "Can or have lakes been acidified by acid deposition?," but instead answer, "How much acidification can or has occurred, and to what degree is it reversible?" By how much is meant how many lakes have changed from one give pH value to another. A half unit decrease of pH in a pH 7.5 lake would probably be biologically insignificant, while a half unit decrease in a pH 5.5 lake could have major biological consequences.

Integration, as used in ILWAS, refers principally to the conceptual or theoretical integration of the multiple factors--climate, deposition, soil, geology, plant, hydrology, limnology--that interact to determine the acid-base status of lakes and streams. Precipitation follows various pathways through a watershed before it reaches a lake. Biogeochemical processes acting in series and in parallel on a landscape level produce and consume acids and release chemicals that shift the pH and alkalinity of natural waters. Scientific investigation of a single process or of several processes independently (that is, within a non-integrated framework) is not sufficient for understanding the complex chemical behaviour of precipitation as it becomes lake water. The results of one process are often modified by others to yield results that are counter-intuitive and conflicting.

What is true of surface water acidification is also true of many other environmental phenomena; that is, system response is governed by the interaction of multiple factors. A plant's response to a gaseous pollutant is mediated by the interaction of a host of atmospheric, plant, and soil factors. Hence, to analyze system response to different management practices, one needs a holistic theoretical framework that explicitly integrates all pertinent variables and processes. For instance, if, for the problem of lake acidification, one fails to account for the possibility of alkalinity generation as the result of the reduction of strong acid anions in lake sediment, then the response of lakes with long residence times to atmospheric inputs of acidity will be incomprehensible.

A model serves many purposes in an integrated environmental research study (Goldstein et al. 1984) such as ILWAS (Gherini et al. 1985):

1. Concept and theory integration--the model is the major vehicle for carrying out integration; this alone justifies its inclusion in the study.
2. Resource organization--the model may be used to determine what disciplines should be represented in the research team, and how resources (time, money, and manpower) should be distributed among the various facets of the study. This is accomplished by using the model to judge which ecosystem components and linkages are most essential to meet the study's objectives.
3. Data synthesis and analysis.
4. Conceptual consistency and hypothesis testing.
5. Extrapolation and interpolation of data (response mapping) to other sites.
6. Prediction of future and estimation of past ecosystem behaviour.
7. Development and analysis of ecosystem management strategies--this function can be related to either optimization of multiple uses (e.g., a forest can be used for recreation and a source of lumber), maximization of sustained yield of a

specific resource (natural or human introduced), or mitigation of effects of anthropogenic perturbations (e.g., liming to mitigate lake acidity).

A mathematical model provides a quantitative framework for the study in a language (mathematics) that minimizes ambiguity and is universal. An important design element (Figure 2) of a study such as ILWAS is the concurrent execution of the modelling and experiments which allows feedback between the two and modification of both during the study period.

Most environmental assessment problems are not amenable to short-term research. Given the complexity of ecological phenomena involved, a long-term plan of no less than 5 years is necessary. This plan should have both well-defined objectives and scope so that the study maintains a sharp focus.

An interdisciplinary research team is needed to contribute experience and expertise from multiple disciplines and give proper balance to the study. Researchers whose experience is in a single discipline will, even if they realize the interdisciplinary nature of a problem, tend to give undue weight to their own discipline. Disciplines relevant to ILWAS included meteorology, plant ecology, soil science, geology, hydrology, limnology, and aqueous chemistry. Success depends not only on assembling a group of interdisciplinary researchers but having them function as a team. It is essential for the researchers to interact with one another in an integrated manner. The model supports such an approach because it permits each participant to see how his work interfaces with that of the other participants.

3. APPLICATION TO MANAGEMENT

In the previous section, the different uses of modelling within an integrated research program were discussed. The completed model potentially has several management applications. It can be used for assessment, research, education, and communication. The ILWAS model can be used not only to study surface water acidification, but also acid deposition effects on fish and forest trees, since the model simulates the chemical environment of fish, deposition to the forest canopy, and chemical concentrations of soil water in the rooting zone.

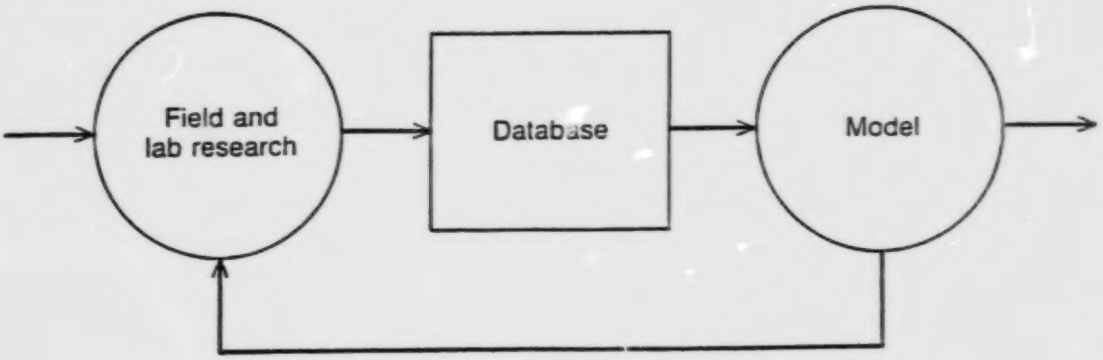
Field and lab research
Database
Model

Figure 2. Research design of the Integrated Lake-Watershed Acidification Study (ILWAS) showing the connection between field and laboratory research, the unified data base, and the model.

With respect to assessment, the ILWAS model can be used to simulate either the response of lake-watersheds to different levels of deposition acidity or the response to different ecological mitigation strategies. Gherini et al. (1985) have discussed simulations of the first type. In this paper, we will illustrate how the model can be used to analyze ecological mitigation strategies.

One currently employed mitigation procedure for acid lakes is neutralization by the addition of a base such as $CaCO_3$ (lime) directly to the lake (Fraser et al. 1982). The resulting neutralization of course is not permanent. The frequency of application needed to maintain neutralization depends on residence time of water in the lake as well as other factors. For lakes with short residence times, it might be advantageous to lime the entire watershed (the terrestrial part as well as the lake) instead of just liming the lake, since the former could significantly decrease the frequency of application. The ILWAS model can be used to simulate the consequences of these two strategies.

Simulations presented in this section are for Woods Lake. The addition of $CaCO_3$ to the lake or the entire catchment is simulated by introducing the $CaCO_3$ as dry deposition on the day of application. It is assumed that the $CaCO_3$ is applied as sufficiently fine particles that it is instantaneously soluble in water.

Woods Lake, as stated before, is an acid lake whose outlet pH is usually between 4.5 and 5.0 (Schofield et al. 1985). The watershed area is 2.1 km^2 of which 0.26 km^2 is covered by the lake (Goldstein et al. 1985). Deciduous forest covers almost the entire terrestrial portion of the watershed. There are some coniferous communities as well (Cronan 1985). Bedrock is granitic. Soils are developed mainly on glacial till and their upper layers are strongly acid. Average depth to bedrock is approximately 2.3 m. Quartz and K-feldspar are the most abundant minerals in the till (April and Newton 1985). Mean water residence time in the lake is 7.3 mo (Peters and Murdoch 1985). Average annual precipitation is about 126 cm, with an average pH of about 4.1 (Johannes et al. 1985).

Before comparing lake to watershed liming, it should be noted that since lake outflow and lake stratification vary seasonally, the expected hydrologic residence time of a marker placed into the lake will vary with location and time of placement. For instance, since the lake is stratified near the surface at the time of snowmelt (Schofield et al. 1985) when maximum outflow occurs, a marker deposited on the surface of the lake at this time will have minimum residence time compared with either a marker placed at the bottom of the lake at the same time or a marker placed at the surface at some time other than during ice cover. The implication for management is that liming is more effective after instead of before snowmelt in the spring, because the lake will be destratified after snowmelt and lime will be distributed throughout the entire water column. When the lime is added before snowmelt, it will tend to be concentrated in the upper part of the water column and be readily flushed from the lake.

Figure 3 compares simulations of the outlet pH of Woods Lake for the case where the lime has been applied at the end of January (1979 January 31), when the lake is covered with ice and stratified, to the case where the lime has been applied at the end of May (1979 May 30), after snowmelt and ice-out. The spring liming results in a higher summer pH which persists for a longer time period within years and also for a greater number of years. Hence, for spring liming, Woods Lake exceeds pH 6 for the next three summers, and the length of time it exceeds 6 in the second summer is less than the time it exceeds 6 in the third summer after spring liming.

Figure 4 compares ILWAS model simulations of the outlet pH of Woods Lake for the case where lime is applied only to the lake and the case where lime is applied only to the terrestrial portion of Woods Lake watershed. In both cases, the liming is done in spring (1979 May 30) and the areal application loadings (1680 meq m^{-2} of $CaCO_3$) are the same; thus, the total amount of lime applied to the land is greater than that to the lake due to the larger land area. The application loading is that which was used in a real liming of Woods Lake.

Outlet pH responds much faster to lake liming; however, the response to terrestrial liming lasts longer. Hence, the first summer after lake liming, pH rises above 6, while for terrestrial liming, the pH does not rise above 6 until the second summer. However, 12 summers after terrestrial liming, the pH is still rising above 6, while for lake liming, the pH does not rise above 6 after the third summer. It should be noted, with respect to

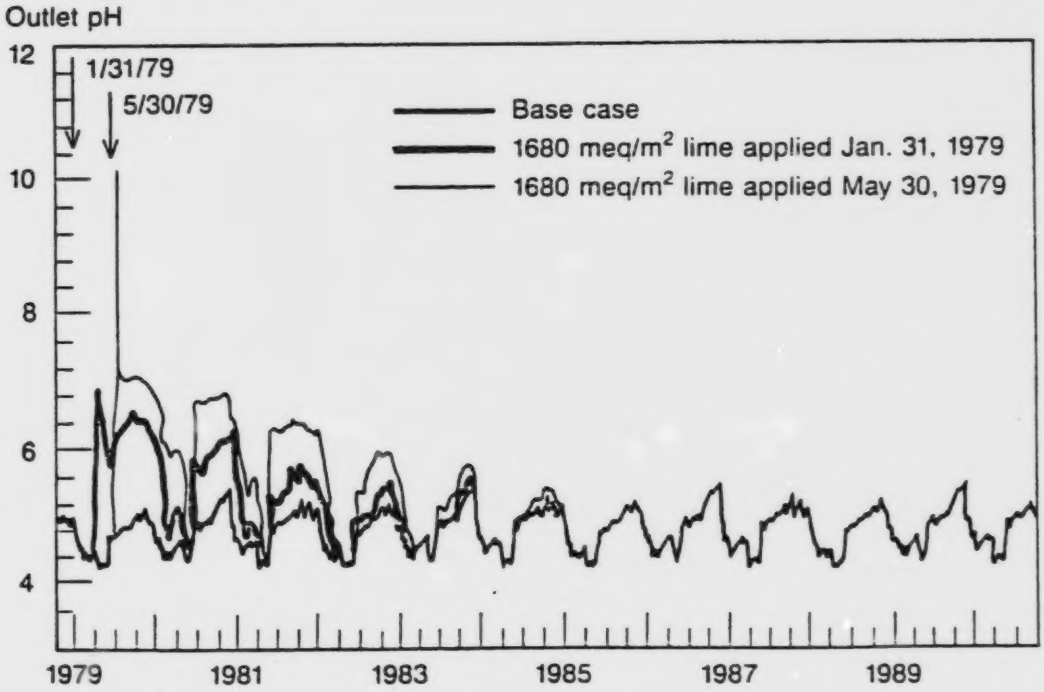

Figure 3. ILWAS Model simulations comparing outlet pH of Woods Lake for winter liming (1979 January 31), spring liming (1979 May 30), and no liming (base case).

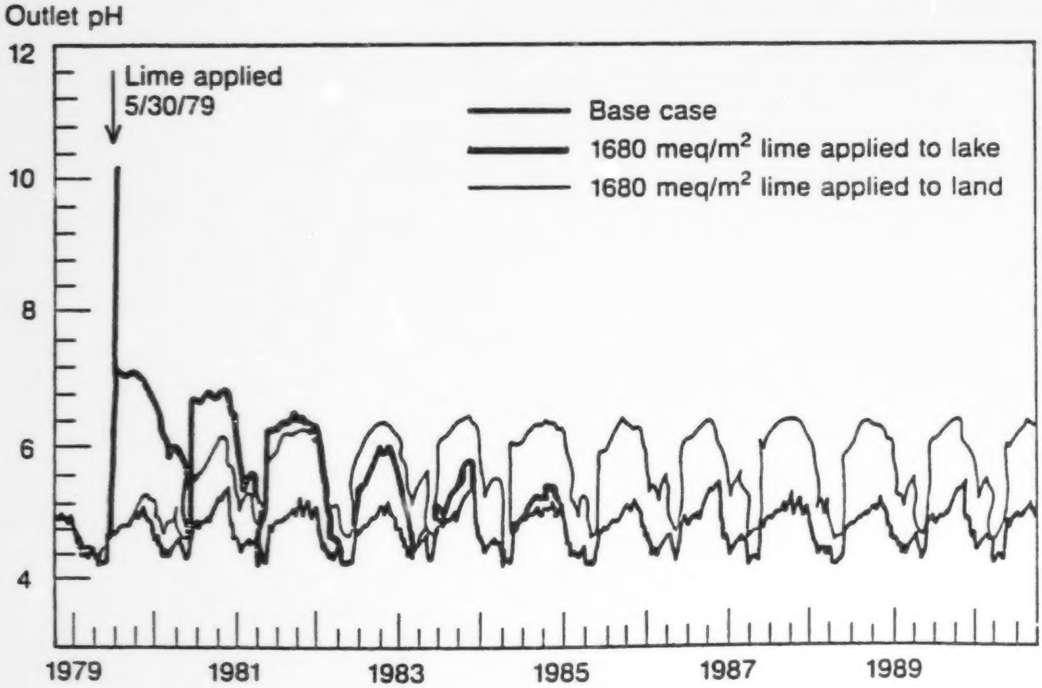

Figure 4. ILWAS Model simulations comparing outlet pH of Woods Lake for lake-only liming, terrestrial area-only liming, and no liming (base case).

Figures 3 and 4, that the outlet waters during stratification are representative of the surface waters of the lake and not necessarily the whole lake. Hence, while the lake is still under the influence of lime, the minimum outlet pH simulated during spring snowmelt will be lower than the pH for lake waters below approximately 1 m. The ILWAS model simulates lake pH at different depths as well as lake outlet pH.

The reason that liming the terrestrial system provides extended neutralization to the lake is that the added calcium adsorbs to the exchange sites in the soils, and then is gradually released to the soil water and ultimately the lake over a long period of time. It should be remembered though that more lime was added to the terrestrial system than to the lake. In making a management decision regarding a choice between the two strategies, the manager would have to factor this into his cost estimates.

Before resource management decisions regarding alternate management strategies are based on the ILWAS model, its ability to simulate responses to liming should be field tested. Plans to do this are being formulated at present. The current version of the model does not include two phenomena which could be important and which field experiments might indicate should be added to the model. The first is possible incorporation of calcium into the lake sediments with possible later release to the lake. Such a phenomenon could increase the effective period of time for which lake liming would produce an elevated lake pH. The second phenomenon is the possible stimulation of tree growth as a result of liming. This would result in an increased fraction of the added calcium being incorporated into biomass and a decrease in the calcium stored on soil exchange sites. Hence, the rate of release of calcium from the terrestrial system to the lake and the resulting pH increase could be less.

4. ANALYSIS OF UNCERTAINTY

What a resource manger needs to know is the probability that an effect will be a certain magnitude, or, perhaps more importantly, the probability that an effect will exceed a certain magnitude.

One of the major conclusions of ILWAS (Goldstein et al. 1985) was that the response of lake-watersheds, within a geographical region, to the same level of acid deposition could be highly variable. The variability would result from variation in biogeochemical and hydrologic characteristics. An assessment of the vulnerability of a region to acidification by atmospheric deposition would take the form of a frequency distribution of responses based on separate classes of lake-watersheds. In a region containing many lakes, it would not be feasible to measure all significant characteristics for each watershed in order to assign it to a class. Hence, the distribution of vulnerabilities would have to be based on probability estimates.

Assessment of effects of environmental perturbants at the organism, population, or ecosystem level of organization is highly complex. Mathematical models are needed to quantify and integrate the multiple system processes and components that interact to determine effects. These models should be ultimately developed in a probabilistic context that explicitly incorporates the different sources of uncertainty inherent in assessing ecological effects. Sources of uncertainty include variation in design amongst experiments, uncertainty in model structure relative to reality, measurement error, intra- and interspecific variation, and spatial and temporal variation in environmental conditions.

If an appropriate probability function for the magnitude of an ecological effect can be estimated, then an analysis of how the sources of uncertainty affect the probability function will result in a more realistic assessment and an understanding of how additional research can decrease the uncertainty in the assessment. For only a few simple models will analytic approaches be feasible. Complicated multi-variable, multi-parameter models will require analyses based on Monte Carlo procedures.

5. CONCLUSION

Current environmental concerns of society are very complex and require sophisticated technical analysis for proper management decision making. A new type of environmental research approach, the integrated approach, has recently evolved to provide necessary management tools. Key elements of the integrated approach are: (1) emphasis on mechanisms and processes; (2) quantification; (3) integration; (4) modelling; (5) long-term perspective; (6) interdisciplinary team effort; and (7) analysis of uncertainty.

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THE ALBERTA ACID DEPOSITION RESEARCH PROGRAM (ADRP) OVERVIEW AND STATUS

by

R.L. Findlay[1] and C. Primus[2]

ABSTRACT

The year 1985 marked the initiation of one of Canada's most ambitious scientific research programs into the environmental effects of acid-forming gases on the health of the people and the environment of Alberta, Canada. After several years of formative discussions, an agreement was signed between the Province of Alberta, the Canadian Petroleum Association, Electrical Utilities, and Alberta's independent Energy Resources Conservation Board establishing the Acid Deposition Research Program (ADRP).

This program of research, which committed $8 million (Canadian) over 7 years, entails several unique features which set a useful precedent for large-scale (regional) investigations in other parts of the world.

Firstly, funding has been provided to university and private-sector laboratories to investigate potential biological and human health impacts from ambient air emissions that are primarily in the SO_x and NO_x forms.

Secondly, an internationally respected group of scientists has been assembled as a science advisory board to provide continuing advice and scientific peer reviews throughout the life of the program.

As such, the ADRP is a unique endeavour involving a large team of scientists and physicians actively co-operating with the industrial, government, and public interests to address the critical societal concern of the impacts of acid-forming gases on Alberta's people and their environment.

This paper discusses the administrative structure of the ADRP. It also provides a status of the biophysical and human health components of the program.

Insights regarding the involvement of independent, scientific review boards and the use of public participation are also discussed.

[1] Industry Co-Chairman, ADRP. Manager, Environmental Affairs, Amoco Canada Petroleum Co. Ltd., Calgary, AB

[2] Government Co-Chairman, ADRP. Assistant Deputy Minister, Alberta Environment, Edmonton, AB

ACKNOWLEDGEMENTS

In a multi-disciplinary research program, such as the Acid Deposition Research Program, many individuals contribute to the success of the research. In particular, thanks are expressed to all the associated individuals of the Members' Committee. Drs. Allan Legge and Walter O. Spitzer, Principal Investigators, provided the expertise for the programs to proceed, as did Ms. Jean Andryiszyn, Communications Officer. The Public Advisory Board, under Dr. Martha Kostuch, provided ongoing, useful advice and counsel, as did the members of each of the Science Advisory Boards (Biophysical and Human Health).

1. INTRODUCTION

The province of Alberta is Canada's single most important site of hydrocarbon production encompassing abundant natural gas, light gravity and heavy crude oil, oil sands, and coal.

It is geographically isolated from the world's major population belts. The province's 660 441 km^2 (255 000 mi^2) are inhabited by 2.3 million people. About 1 in 10 Canadians lives in Alberta. The 1981 national census showed 77% of Alberta's population residing in urban centres, with well over half of the total in the cities of Calgary and Edmonton. In area, the province surpasses the combined total of Great Britain, Denmark, and West Germany, nations occupying similar latitudes in Europe. The provincial climate is dry and sunny. Alberta's oil and gas reserves extend to all boundaries of the province.

In 1984, Alberta's 17 600 oil wells produced 164 000 $m^3 \cdot d^{-1}$ of crude oil. Over 10% of the province's total oil production (7.8×10^6 m^3) originated with two oil sands mines in northeast Alberta. As well, 4.9 million tonnes of coal were mined for trans-shipment to offshore markets.

Over half of the existing natural gas production contains hydrogen sulphide gas--a gas that must be removed as elemental sulphur before the natural gas may be marketed.

Alberta standards for sulphur removal are among the highest achieved in the world (97 to 98% recovery). Nonetheless, given the large rates of production, more than 815 555 $t \cdot yr^{-1}$ (Behie et al. 1980) of acid-forming gases, primarily in the NO_x and SO_x forms, are released to the atmosphere. Concerns expressed over the potential long-term effects in Alberta and those effects transported to neighbouring provinces are to be addressed through the Acid Deposition Research Program (ADRP). The research program represents a recognition by government, industry, public, and private sectors of the need to encourage regional studies into long-term effects, so as to maintain or enhance the quality of life in Western Canada.

As Alberta is at present the largest emitter of SO_x and NO_x among the four Western Canadian provinces, it has taken exceptional steps to study and address the environmental consequences of acid deposition.

The volume of these emissions, and the growing attention to problems resulting from the effects of acidification across North America, led to the early development of major research programs in the province.

The ADRP is among the recent and certainly one of the most ambitious in its range and scope.

2. THE PROGRAM

The ADRP is unique in its source of funding and its approval process. The Alberta Department of the Environment contributes 50% of all funds while the Canadian Petroleum Association contributes 34.4%. The Energy Resources Conservation Board and the Electrical Utilities Industry contribute 10% and 5.6%, respectively. An 88% vote from the funding members is required for program approval.

The ADRP also combines the scientific managerial resources of government, academia, industry, and the private sector in a structure which is set out to ensure the maximum productivity of science in a highly compressed time frame. Further, the program attempts, for the first time, to integrate research efforts in both the biophysical and human health disciplines under one study.

To preserve 'scientific balance,' an internationally respected group of environmental and medical scientists provides continuing advice and peer reviews through two science advisory boards. In recognition of the value of public views of the program, a public advisory board has been formed to facilitate involvement from, and communication with, the general public and environmental interest groups.

The ADRP is, therefore, a singular experiment in which terms of scientists, physicians, and environmental advisers actively co-operate with industry, government, academic, and private sector researchers in a program with high public visibility and input from many different source points.

The program is organized under the direction of a members' committee chaired jointly by an industry and a government representative. Other representatives of the committee are drawn from the utilities industry, the Energy Resources Conservation Board, and the public at large (Figure 1).

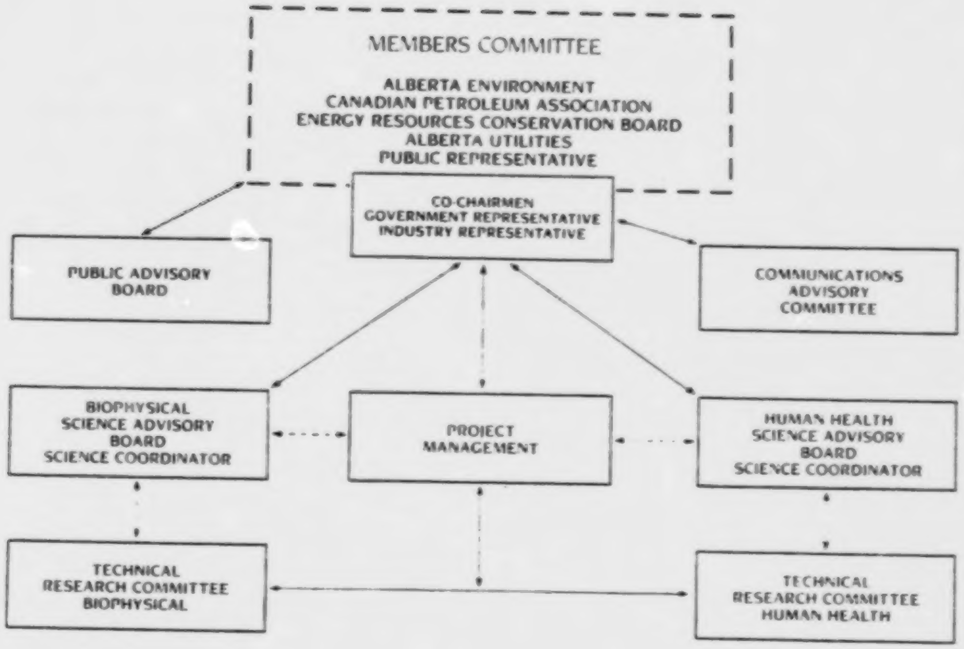
MEMBERS COMMITTEE
ALBERTA ENVIRONMENT
CANADIAN PETROLEUM ASSOCIATION
ENERGY RESOURCES CONSERVATION BOARD
ALBERTA UTILITIES
PUBLIC REPRESENTATIVE
CO-CHAIRMEN
GOVERNMENT REPRESENTATIVE
INDUSTRY REPRESENTATIVE
PUBLIC ADVISORY BOARD
COMMUNICATIONS ADVISORY COMMITTEE
BIOPHYSICAL SCIENCE ADVISORY BOARD SCIENCE COORDINATOR
PROJECT MANAGEMENT
HUMAN HEALTH SCIENCE ADVISORY BOARD SCIENCE COORDINATOR
TECHNICAL RESEARCH COMMITTEE BIOPHYSICAL
TECHNICAL RESEARCH COMMITTEE HUMAN HEALTH

Figure 1. Alberta Government/Industry Acid Deposition Research Program organization.

2.1 BIOPHYSICAL COMPONENT

Early in 1985, the University of Calgary, Kananaskis Centre for Environmental Research and a host of private sector research companies were selected to undertake work to reach the first 'critical point' of the Biophysical Research Program under the direction of Principal Investigator, Dr. Allan Legge, Senior Professional Associate, the University of Calgary.

The Phase I contract is valued at $2.9 million and will span a period of 32 months, with completion slated for 1987. The intent of this phase is to compare the regional airshed sample results from a transportation corridor and an industrial and an urban plume with the overall air quality parameters and for air entering the province. The work is focused within three major categories:

1. An inventory of sulphur oxide and nitrogen oxide emissions in Alberta;
2. Air quality assessments; and
3. An initial assessment of potential impacts of acid deposition within Alberta.

Three site locations have been selected in environmentally sensitive areas in order to monitor air quality parameters. A 'background site' at Fortress Mountain, 100 km west of Calgary, Alberta, has been selected to provide baseline data on air entering the province from the neighbouring province of British Columbia and the western seaboard. Two sites in the Crossfield region (30 km north and northeast from Calgary) were selected as 'downwind' and 'regional' monitor sites. The downwind site is situated to receive emissions from gas plant operations, urban sources, a transportation corridor, and several small towns and villages. The Crossfield sites were chosen after exhaustic analyses in conjunction with site selection criteria, that included ideal meteorological conditions, flat terrain with a uniform fetch, and good proximity to local emission sources. The chemical parameters being monitored are noted in the following list:

- SO_2
- H_2S
- NO
- NO_2
- NO_x
- CO_2
- O_3
- COS
- CS_2
- Hydrocarbons
- Coarse and Fine Particulates
- NH_3
- HNO_2
- HNO_3
- Stable Isotopes
- Wet Deposition (Rain)

Other aspects of the study include sampling of major point source emission stacks at industry sites for oxides of nitrogen and oxides of sulphur and development of a complete inventory of these sources in the province.

An ambitious worldwide literature review is to provide a comparative basis for a 'first order' assessment of the current status and future potential of acidification in Alberta.

Air quality data are to be synthesized and combined with the output from the biological and literature research, resulting in a final report for Phase I that will be used to form the basis for additional research programs.

2.2 HUMAN HEALTH COMPONENT

On 1985 May 01, Alberta's Minister of Social Services and Community Health announced that the ADRP, on behalf of the Government of Alberta, had awarded the Medical Diagnostic Review to McGill University of Montreal, Quebec, Canada. This $3.5 million project is in addition to the $8 million research program.

The project is designed to address the specific and long-standing health concerns of residents of the southwestern towns of Twin Butte, Mountain View, Hillspring, and Glenwood, and to determine, in a conclusive manner, whether these residents experience health problems in greater or lesser measure than do residents of other Alberta communities. Although the study will not address cause-effect relationships, resident concerns centre around living in a downwind corridor of a major gas processing facility. The field work required more than 90 medical and support personnel to spend 10 wk in the area in the summer of 1985.

As Principal Investigator, Dr. Walter O. Spitzer, Head of Epidemiology at McGill University and of the Montreal General Hospital's Rapid Response Unit, led an inter-university and international group of scientists and clinicians. The use of personnel from several organizations was necessary because no one university or research organization had the expertise to tackle such a complex problem within the time frame allocated for the research.

Scientific evaluation of the McGill proposal was conducted by a panel of independent senior investigators from several universities in North America who made their recommendations to the ADRP. In addition, Dr. Spitzer formed a community advisory group of lay residents and elected officials to counsel him and his colleagues concerning public participation and questions of relevance. The group was formed in May 1985 from persons nominated by interest groups in the communities studied.

This multi-phase research program relied upon a comprehensive health assessment by questionnaire and was followed by full physical examinations involving more than 90% of all residents. In-depth and ultra-specialized testing of those residents who displayed unexplained health problems was also conducted. Parallel measurements were implemented in two comparison communities in exactly the same manner, again exceeding 90% participation levels.

More than 3600 people voluntarily participated in the program from June through August 1985. Dr. Spitzer and his team are now analyzing the data at their research facilities at McGill Universtiy, as well as implementing out-migrant surveys. A report on their findings is expected in mid-1986.

In addition to the Medical Diagnostic Review, an occupational epidemiology feasibility study is underway to determine the scientific merits and constraints of further research. This research area, which will focus more specifically on the occupational work force of the sour gas industry, will attempt to determine whether acute or chronic exposure to sour gas or its by-products has significantly affected the health of workers. The outcome of these two human health projects will determine whether a more comprehensive community epidemiological study is required to investigate the public concern between ill health and acid-forming emissions.

2.3 PUBLIC ADVISORY BOARD

The Public Advisory Board (PAB) was established in the spring of 1935 as a reflection of the ADRP's commitment "to encourage and include opportunities for public participation and representation."

The PAB consists of six members representing agriculture, health care, environmental groups, municipal districts and counties, a voting member of the ADRP's Members' Committee, and a member of the general public.

The PAB's mandate is to provide a broad spectrum of public input to the Members' Committee, exchange information, and offer advice on public involvement, information, and communications. An elected PAB member sits as a non-voting member of the ADRP's Members' Committee.

3. SUMMARY AND CONCLUSIONS

The ADRP is one of the most ambitious research undertakings on acid-forming emissions in North America. In the relatively brief period since the formal inception of studies in early 1985, significant advances have been made in deploying a highly sophisticated atmospheric monitoring system and in accomplishing the field research component of the Medical Diagnostic Review.

The ADRP looks forward to maintaining this momentum of research and to completing successfully its objectives:

1. To provide a comprehensive understanding of the effects and consequences of acid-forming gases on the environment;
2. To provide a scientific basis for sound, long-term environmental management and regulatory control with respect to acid-forming gases;
3. To disseminate such information among members, to the public, and to government bodies;
4. To undertake any research deemed appropriate; and
5. To encourage and include opportunities for public representation in the ADRP.

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ACID DEPOSITION: RESEARCH, MONITORING, AND MANAGEMENT STRATEGY IN WESTERN AND NORTHERN CANADA

by

R.G. Wilson[1] and H.S. Sandhu[2]

ABSTRACT

This paper presents an overview of the joint government program for acid deposition in Western and Northern Canada. The program's objectives, organization, and accomplishments are outlined, and the resource management strategy is discussed.

[1] British Columbia Ministry of the Environment, Victoria, BC
[2] Research Management Division, Alberta Environment, Edmonton, AB

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The authors wish to thank other members of the Technical Committee for the Long Range Transport of Atmospheric Pollutants (LRTAP)/Acid Deposition in Western and Northern Canada: Dr. M. Morelli, Manitoba; Mr. L.J. Lechner, Saskatchewan; Mr. M. Smith, Northwest Territories; and Mr. D.A. Faulkner, Atmospheric Environment Service, for supplying information and reviewing this paper.

1. INTRODUCTION

The national and provincial governments of Canada have a tradition of joint action on environmental issues, resulting in cost-effective research and monitoring programs and a uniform approach to problems regardless of provincial boundaries. The acid rain program in Western and Northern Canada is a good example.

British Columbia, Alberta, Saskatchewan, Manitoba, Northwest Territories, and Canada first held joint consultations on the acid rain issue in 1980 and by 1982 had formalized a joint action plan by signing a 3-year research and monitoring program. In 1985, this program was renewed for a further 3-year period (Technical Committee for the Long Range Transport of Atmospheric Pollutants in Western Canada 1981, 1982, 1983, 1984, 1985).

In 1980, very little was known about the acid rain issue in Western Canada. Precipitation chemistry data from a sparce regional network of federal stations suggested that acid deposition was not a serious problem, but the serious environmental impacts occurring in Eastern Canada provided a strong incentive to develop a better scientific information base. As a result of these various factors, a strongly structured, goal-oriented program was developed to produce the maximum amount of information in a reasonably short time frame and to develop control strategies for acid deposition.

The intent of this paper is to outline the framework and general approach which has been taken and to provide an indication of future direction.

2. PRINCIPLES FOR CO-OPERATIVE ACTION

The governments of British Columbia, Alberta, Saskatchewan, Manitoba, the Northwest Territories, and Canada have recognized the potential for harm from acid deposition in some parts of Western and Northern Canada and, with the understanding that control of acid rain is a provincial responsibility, have agreed upon certain principles for co-operative action:

1. To maintain a high standard of air quality throughout Western and Northern Canada;
2. To protect sensitive areas through possible control actions in adjacent provinces;

3. To work towards harmonized air quality standards where appropriate;
4. To develop an integrated air quality monitoring network;
5. To freely exchange scientific, technical, and monitoring data; and
6. To co-operate on scientific activities such as the establishment of scientific criteria for sulphate, nitrate, and hydrogen ion target loadings; the monitoring of air quality trends; and the identification of areas sensitive to pollutant deposition.

This co-operative action is intended to provide research and monitoring information to be used for the development of management strategies in each jurisdiction so that environmental damage due to acid deposition is minimized. Both the research and the management components are described below.

3. RESEARCH AND MONITORING PROGRAM

3.1 OBJECTIVES

In 1982 and again in 1985, the governments of Western and Northern Canada signed 3-year agreements supporting a structured research program. The program objectives are:

1. To collect and organize data to identify baseline conditions and major components of environmental systems requiring research;
2. To identify, analyze, evaluate, and predict effects of industrial development on the environment;
3. To establish research and monitoring priorities and to devise, initiate, and manage research projects which will yield the necessary knowledge for effective management and regulation practices;
4. To integrate and co-ordinate all research activities related to acid deposition in the environment in Western and Northern Canada;

5. To publish all relevant scientific information which could be used to minimize adverse environmental effects; and
6. To promote the establishment of mechanisms which will assist the translation of research results into operational practices to serve the objectives of the appropriate government agencies.

3.2 ORGANIZATION

The overall direction and program approval are provided by a Consultative Committee comprised of senior officials of each participating agency (Figure 1). The program is planned and implemented by a Technical Committee of agency representatives, and annual reports have been published since 1981 highlighting individual projects undertaken by governments, industry, and institutions. Ties are maintained with both the national acid rain program and activities in the United States.

3.3 1982 AND 1985 AGREEMENTS

The program priorities for the 1982 agreement are shown in Table 1 together with some of the major accomplishments. A quick scan of the six major priorities, all of which are obvious and rather basic questions, gives a good indication of just how scarce our information was at the start. For example, British Columbia initially had useful data from which to determine lake sensitivity from only 160 lakes (Western Canada LRTAP Committee on Surface Water 1982), but by the end of 1985, over 700 lakes had been sampled (Swain 1985).

During the 1982 to 1985 agreement, methodologies were prepared for the sensitivity mapping (Western Canada LRTAP Committee on Surface Water 1982; Western Canada LRTAP Task Group on Soil and Geology Sensitivity Mapping 1982) and precipitation monitoring (McQuaker et al. 1983) so that information collected or prepared by individual provinces or territories would be directly comparable. Other methodologies for emissions (Western Canada LRTAP Air Emission Inventory Working Group 1986) and surface water monitoring are being pursued at the present time. Sensitivity maps were prepared for aquatic, soil, and geologic environments and will be presented at this symposium. Precipitation monitoring was expanded significantly and new

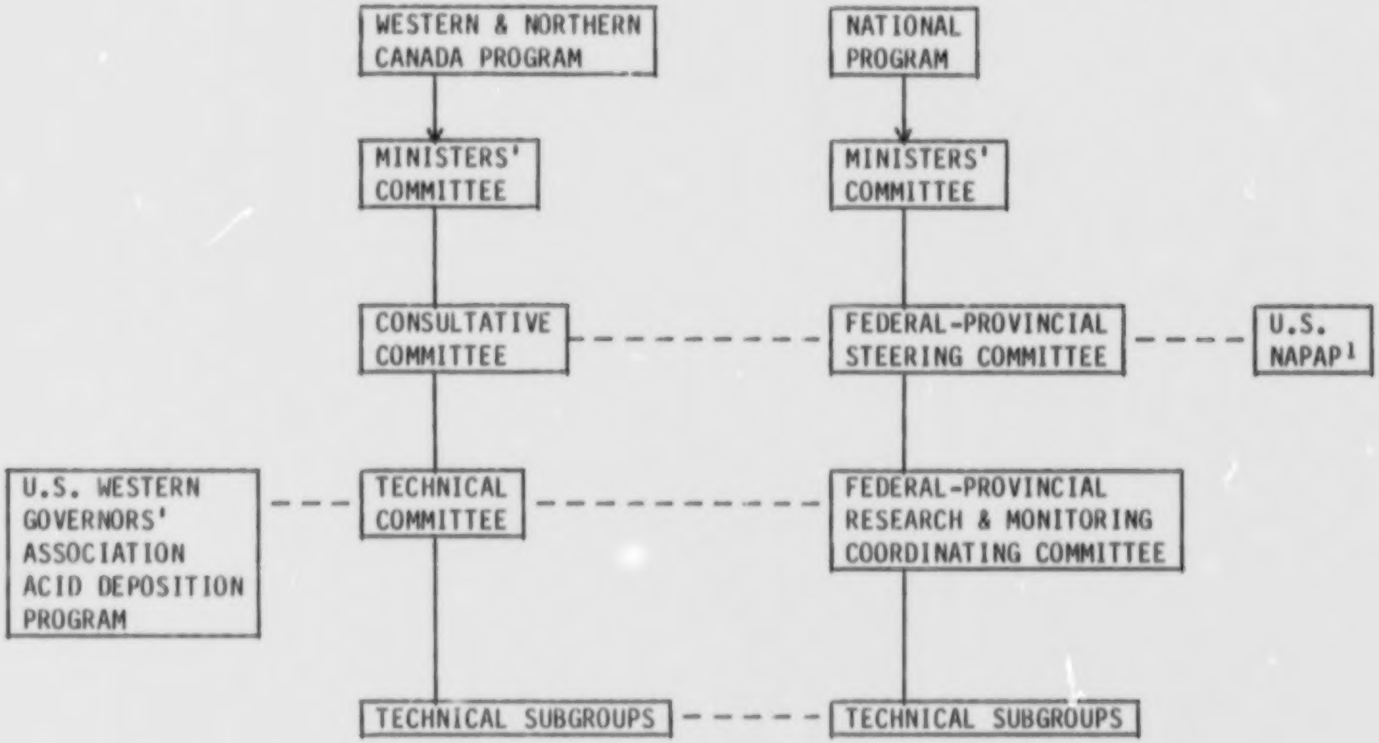
WESTERN & NORTHERN CANADA PROGRAM
NATIONAL PROGRAM
MINISTERS' COMMITTEE
MINISTERS' COMMITTEE
CONSULTATIVE COMMITTEE
FEDERAL-PROVINCIAL STEERING COMMITTEE
U.S. NAPAP¹
U.S. WESTERN GOVERNORS' ASSOCIATION ACID DEPOSITION PROGRAM
TECHNICAL COMMITTEE
FEDERAL-PROVINCIAL RESEARCH & MONITORING COORDINATING COMMITTEE
TECHNICAL SUBGROUPS
TECHNICAL SUBGROUPS

Figure 1. Organization of the National and Western and Northern Canada programs for acid rain/ long range transport of atmospheric pollutants (LRTAP).

([1]National Acid Precipitation Assessment Program)

Table 1. Research and monitoring program priorities for 1982 to 1985 and accomplishments.

- MAPS OF AQUATIC SENSITIVITY
    - methodology prepared and published (Western Canada LRTAP Coordinating Committee on Surface Waters 1982)
    - preliminary maps completed
- MAPS OF SOIL AND GEOLOGY SENSITIVITY
    - methodology prepared and published (Western Canada LRTAP Task Group on Soil and Geology Sensitivity Mapping 1982)
    - preliminary maps completed
- MONITORING BACKGROUND PRECIPITATION
    - standardized protocol developed and published (McQuaker et al. 1983)
    - monitoring programs expanded to 62 stations
- MODELLING OF ATMOSPHERIC DEPOSITION PATTERNS
    - applied long-range model
    - mesoscale workshop
- EMISSION INVENTORIES OF SULPHUR DIOXIDE AND NITROGEN OXIDES
    - regularly updated
    - common methodology being pursued (Western Canada LRTAP Air Emission Inventory Working Group 1986)
- MONITORING OF SURFACE WATERS AND SOILS IN DATA SPARCE AREAS
    - major increase in data available
    - common methodology for water sampling being pursued

efforts were made to collect data on acid gas emissions and remote surface waters and soils.

The priorities for the 1985 to 1988 program, shown in Table 2, provide for continuation and tailoring of the monitoring activities for parameters considered to be of special significance in Western Canada; for the establishment of deposition standards suitable for the sensitivity of our environment; and for investigation of deposition models and control models, which will allow evaluation of the impact of individual sources, and the most cost effective manner of implementing a control program potentially involving several sources.

4. THE MANAGEMENT STRATEGY

The acid deposition management strategy adopted by the western provinces is, very simply, to prevent damage to the environment and has four basic elements:

1. Determine the sensitivity of our environment to acid deposition;
2. Establish target loadings which are suitable for the sensitivity of our environment;
3. Monitor to ensure compliance with the targets; and
4. Establish emission management plans as necessary.

4.1 SENSITIVITY MAPS

Sensitivity maps have been prepared for soil, geologic, and aquatic systems using uniform protocols (Western Canada LRTAP Task Group on Soil and Geology Sensitivity Mapping 1982; Swain 1985). Significantly, this mapping activity has identified major areas which are highly sensitive to acid deposition. A total of 47% of the 520 lakes sampled in Saskatchewan (L.J. Lechner, personal communication) and 20% of the 720 lakes sampled in British Columbia (Swain 1985) have been classified as highly sensitive. Vegetation sensitivity mapping is also being considered.

4.2 TARGET LOADINGS

The federal and provincial governments of Canada have accepted the concept of a 'target loading' based on sulphates to control the deposition of

Table 2. Research and monitoring program priorities for 1985 to 1988.

- MONITORING OF AIR, RAIN, AND SNOW
- EMISSIONS INVENTORY UPDATES
- DEPOSITION CRITERIA/TARGET LOADING FOR WESTERN CANADA
- MEDIUM RANGE TRANSPORT/DEPOSITION MODELS
- BACKGROUND ION CONCENTRATIONS AND THE INFLUENCE OF DUST
- DRY DEPOSITION MEASUREMENTS
- MONITORING OF SENSITIVE SURFACE WATERS AND TERRESTRIAL ENVIRONMENTS
- EVALUATION OF IMPACTS AND ASSESSMENT OF CONTROL TECHNOLOGY

acid pollutants to aquatic ecosystems. A value of 20 kg of wet sulphate per hectare per year was agreed upon for protecting those lakes of Eastern Canada having moderate to low sensitivity to acid deposition. This annual deposition would allow pH to remain above 5.3 for all but the most sensitive aquatic ecosystems (Sandhu and Blower 1986).

In the application of the target loading concept, it is recognized that it is the total deposition, wet plus dry, that really matters. Since the dry deposition is not readily measurable, the target is usually expressed in terms of the wet deposition which is measurable. The wet deposition target loading of 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ is not directly applicable to Western Canadian environmental conditions (Sandhu and Blower 1986). Therefore, it is important to establish a suitable target loading for Western and Northern Canada. This process has been started (Newcombe 1985) and was recently expanded through a contract to the National Research Council, with a report expected in 1987.

4.3 DEPOSITION MONITORING

Precipitation chemistry is now monitored at 62 locations across Western and Northern Canada. Wet sulphate deposition at most locations is less than 10 $kg \cdot ha^{-1} \cdot yr^{-1}$ (see Figure 2) and is above 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ only at one station, Vancouver. Despite the overwhelming tendency toward low deposition values, however, approximately 15% of monitoring stations experience wet deposition greater than 10 $kg \cdot ha^{-1} \cdot yr^{-1}$.

Dry deposition has not been measured on a systematic basis due to the difficulty of the measurement. However, calculations (Kociuba 1984) indicate that it may range between about 5 and 22 $kg \cdot ha^{-1} \cdot yr^{-1}$ at locations in Alberta, with an average for the province of 16 $kg \cdot ha^{-1} \cdot yr^{-1}$.

One of the current difficulties in interpreting sulphate deposition data for monitoring stations in dry climates is to properly account for the role of dust in the total deposition. A similar situation exists in coastal areas due to deposition of sulphate with sea salt, but this neutralized sulphate can be calculated and subtracted due to the presence of the salt. However, no similar mechanism exists to correct for dust.

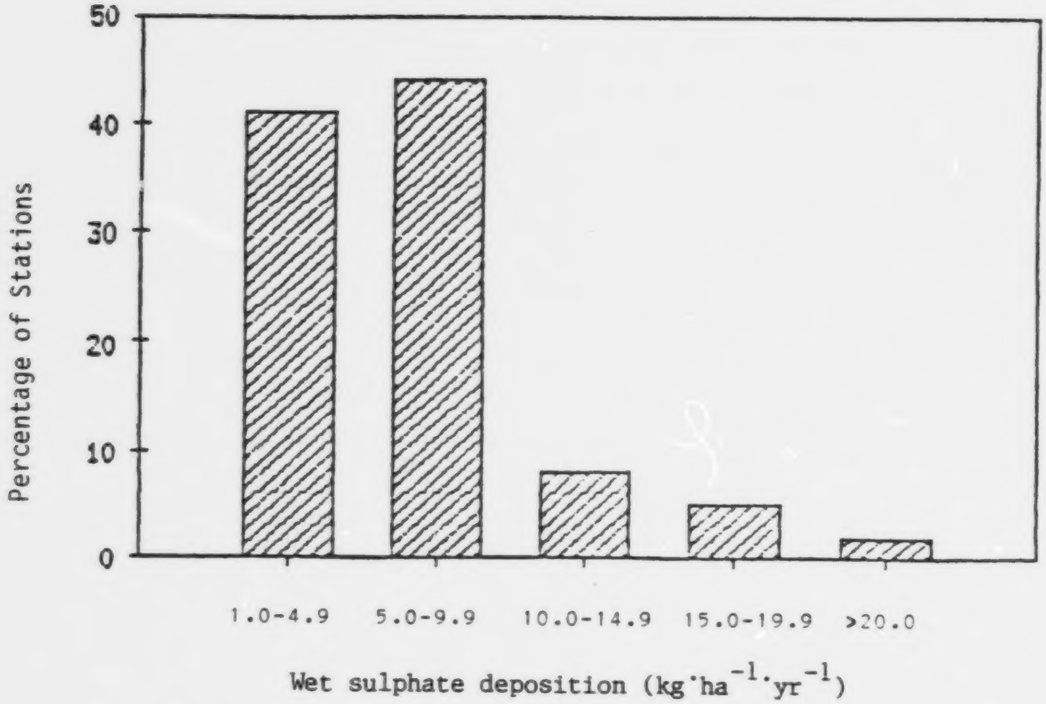

Figure 2. Annual wet sulphate deposition at 39 stations in Western and Northern Canada.

4.4 EMISSIONS MANAGEMENT

Total sulphur dioxide emissions in the four western provinces declined from 1938 kilotonnes in 1972 to 1156 kilotonnes in 1982 (see Table 3), a reduction of approximately 40%. Manitoba currently has an emission ceiling of 738 kilotonnes per year; however, by 1994 the ceiling will be lowered to 550 kilotonnes as part of the sulphur dioxide emission reduction program in Eastern Canada. Other local control programs may have to be undertaken in Western Canada if monitoring indicates that observed deposition rates exceed an acceptable target loading. Additionally, industrial sources of sulphur dioxide have to be screened for incremental impact.

Transport and deposition models usually will be essential to this process, just as dispersion models are critical to evaluating air quality impacts for the more common pollutants. Attempts to use Environment Canada's long-range transport model (Kociuba 1984), which was developed and validated for eastern North America, have indicated that it is not well-suited to Western Canada. Rather, mesoscale models suitable for shorter distances and fewer contributing sources are more appropriate (Western LRTAP Technical Committee and Federal LRTAP Liaison Office 1985; Western Mesoscale Modelling Task Group 1985) and are being actively pursued.

5. CONCLUDING REMARKS

By the end of the current program, the participating agencies will have basic information available on three of the four elements of an acid deposition management strategy; namely, the sensitivity mapping, deposition target loadings, and current deposition rates. With this information, it will be possible to activate the management strategy, although full implementation will require further refinements of our current knowledge. Development of sulphate deposition and economic modelling, a better understanding of dry deposition, the influence of dust in the dry climates of the west, and the pursuit of new control technologies applicable to western industries are the areas requiring attention; all are identified as priorities in the 1985 to 1988 program and may require attention beyond 1988. At the present time, the effects of acid deposition on animal and human health are not important issues in Western and Northern Canada with the

Table 3. Western Canada SO_2 trends (kilotonnes/year).

Province/Year	1972	1976	1978	1982
British Columbia	445	368	231	205
Alberta	807	511	528	488
Saskatchewan	44	41	57	97
Manitoba	642	601	500	366
Total	1938	1521	1316	1156

exception of Alberta, where these aspects are being addressed by the Alberta Government/Industry Acid Deposition Research Program.

The Western Canada program has made important contributions to the national program. We have carried forward issues such as a uniform protocol for precipitation sampling, regional background deposition levels, mesoscale deposition models, and deposition standards for highly sensitive environments.

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AN OVERVIEW OF ALBERTA ENVIRONMENT'S ACID DEPOSITION PROGRAM

by

H.P. Sims,[1] G.A. Singleton,[1] and H.S. Sandhu[1]

ABSTRACT

Relative to Alberta, our knowledge regarding medium- and long-range transport of air pollutants/acid rain and the biological effects of long-term, low-level emissions is presently limited. Some concerns are: (1) acidification of surface waters and the potential consequences for aquatic biota, including fish; (2) acidification of soils and their influence on the total watershed, vegetation, and aquatic systems; (3) direct effects on agricultural crops and forest tree species; and (4) direct and indirect effects on human and animal health.

Alberta Environment established a Departmental Acid Deposition Research Program comprised of four distinct but integrated components:

1. Alberta Environment's acid deposition research program to address the environmental impacts of oil sands development in northeastern Alberta on forest and aquatic ecosystems;
2. The Alberta Government/Industry Acid Deposition Research Program, focussed primarily on agriculture and human health;
3. Western and Northern Canada LRTAP federal/interprovincial program (Long Range Transport of Air Pollutants); and
4. Monitoring of acid-forming emissions.

The program will provide scientific information for evaluating and reviewing Alberta's current air quality standards, emission guidelines, and regulatory controls with respect to socio-economic and environmental consequences of atmospheric pollutants and to satisfy the concerns of Albertans.

The objective of the monitoring program is to monitor precipitation quality, exposure to SO_4 and H_2S in and around urban centres and industrial areas; the potentially adverse effects of atmospheric acid deposition on Alberta's soil resource; and water quality of Alberta rivers and lakes.

The current and future thrusts of research in the atmospheric area are designed to provide scientific information to develop quantitative source-receptor relationships for predicting deposition at short and medium distances from the source (0 to 500 km).

Earlier acid-deposition research demonstrated clearly the high degree of variability in the measurement of ecosystem parameters in forested systems, and the difficulty with measurement of the effects of low concentrations of pollutants. It has become clear in recent reviews that

(Continued...)

[1] Research Management Division, Alberta Environment, Edmonton, AB

a new strategy is required for evaluation of acid deposition effects. This strategy will be to develop biomonitoring indices that will be used to monitor effects of low levels of acid-forming emissions over the long term.

As well, the research program will undertake studies to determine the capacity of the ecosystem to resist detrimental effects. Work will be undertaken on control technologies to reduce emissions at their source.

The Alberta Environmental Centre is undertaking a study on the health effects of sulphur gases. The objective is to determine the effects of toxic, or potentially toxic, gases, vapours, particulates, and aerosols on animals and, by extrapolation, on humans.

Overall co-ordination for the Departmental Acid Deposition Research Program is provided by the Research Management Division with the advice and support of the Departmental Committee on Acid Deposition (DCAD). This committee addresses all activities, including research and monitoring, and provides liaison between the departmental program, LRTAP, and the Government/Industry Acid Deposition Programs.

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1. INTRODUCTION

Acid-forming emissions, such as oxides of sulphur and nitrogen, can be transported from a few to thousands of kilometres. Because of the dramatic, deleterious environmental effects observed at Sudbury, Ontario, Trail, British Columbia, and in the vicinity of many point sources in the United States, it was generally believed that emissions resulted mainly in local environmental impacts. However, scientific evidence has been obtained to show that transport of these emissions occurs over long distances, such as from the Ohio River Valley through the northeastern United States into Eastern Canada; from the United Kingdom into Norway; and from the Ruhr Valley in West Germany into Sweden. Similarly, emissions originating in Alberta are transported to areas downwind of major sources, where ecosystems may be sensitive to acid deposition (Legge et al. 1978; Sandhu et al. 1980). The present and potential impacts of these emissions are not well understood. Some of the concerns are: (1) acidification of surface waters and the potential consequences for aquatic biota, including fish; (2) acidification of soils and their influence on the total watershed, vegetation, and aquatic systems; (3) direct effects on agricultural crops and forest tree species; and (4) direct and indirect effects on human and animal health.

Current emissions of acid-forming substances, their deposition, and potential long-term detrimental effects on the environment have not only become a major scientific issue, but a focus of significant public concern in Alberta. Nevertheless, industrial development is dictated by economic opportunity and cannot wait for long-term research projects to provide all of the answers to possible problems. In many cases, we must rely on judgement and external experiences to allow promotion of development goals without sacrificing critical components of our environment. We are aware that our perspectives of the relationship between environmental quality and industrial development are diverse and vary from region to region. However, the concern for environmental quality has never been higher in our history than at present, and determined efforts by the public to have an influential role in the decisions that affect the fate of our environment are rightfully increasing.

A number of issues and concerns have been identified in the following documents published by Alberta Environment:

1. Proceedings of Alberta Sulphur Gas Research Workshop I. Edmonton, Alberta; 1973 November 01 (Hocking and Reiter 1973).
2. Proceedings of Alberta Sulphur Gas Research Workshop II. Kananaskis, Alberta; 1975 January 16 to 17 (MacDonald and Sandhu 1975).
3. Proceedings of Alberta Sulphur Gas Research Workshop III. Edmonton, Alberta; 1977 November 17 to 18 (Sandhu and Nyborg 1977).
4. Symposium/Workshop proceedings: acid-forming emissions in Alberta and their ecological effects. Edmonton, Alberta; 1982 March 09 to 12 (Alberta 1982).
5. Researching acid deposition: workshop proposals. Canadian Petroleum Association, Calgary, Alberta [Alberta Government/ Industry Acid Deposition Research Program (ADRP) 1984].
6. Western Canada LRTAP Technical Committee. 1981, 1982, 1983, 1984 annual reports (Technical Committee for the Long Range Transport of Atmospheric Pollutants in Western Canada 1981, 1982, 1983, 1984).
7. Alberta Oil Sands Environmental Research Program 1975 to 1980: summary report (Smith 1981).
8. Environmental sulphur research in Alberta: a review (Sandhu et al. 1980).
9. The oxides of nitrogen and their interaction in the environment: a review (Legge et al. 1980).

With the use of emission abatement strategies, local ground-level concentrations have decreased in the vicinity of new stationary sources. However, the potential for long-term, progressive, subtle impact on the environment remains. Relative to Alberta, our knowledge regarding medium- and long-range transport of air pollutants/acid rain and the biological effects of long-term, low-level emissions is presently limited.

Research and monitoring/surveillance programs need to be expanded and implemented to overcome our knowledge deficiencies. To facilitate this, Alberta Environment established a formal Departmental Acid Deposition Program a few years ago. This program is comprised of four distinct but integrated components:

1. Alberta Environment's acid deposition research program.
   This program was developed as a result of a departmental commitment to address the environmental impacts of oil sands development in northeastern Alberta on forest and aquatic ecosystems. In addition, research on inhalation toxicology and animal health is being undertaken at the Alberta Environmental Centre at Vegreville.
2. The Alberta Government/Industry Acid Deposition Research Program (ADRP).
   ADRP was initiated to complement Alberta Environment's departmental program in order to provide a comprehensive program of acid deposition research for the province. Research to date has focussed primarily on the effects of emissions from sour gas and utility industries, in the southern part of the province, on agriculture and human health.
3. Western and Northern Canada LRTAP.
   The departmental program also provides the Alberta focus for the Western and Northern Canada LRTAP federal/interprovincial program (Long Range Transport of Air Pollutants) which investigates the medium- and long-range transport of air pollutants and their possible environmental effects.
4. Alberta Environment's Line Division Research/Monitoring.
   Monitoring of acid-forming emissions is conducted by line divisions within Alberta Environment (e.g., Pollution Control Division, Earth Sciences Division, Standards and Approvals Division). This work is mainly to assist with setting standards and determining compliance with existing regulations.

Some key questions that are addressed by Alberta Environment's acid deposition research program include:

1. What effects do present Alberta emissions have on the environment?
2. Can the effects of future emissions on the environment be predicted?

3. At what point during environmental acidification does significant ecosystem deterioration begin?
4. Are the effects reversible?
5. What mitigative measures can be implemented?
6. What are the best possible management strategies to prevent degradation of environmental quality?

This symposium offers the opportunity to provide an overview of the acid deposition related activities being undertaken by Alberta Environment; an indication of how these activities are integrated to meet total provincial needs; some details of specific research and monitoring activities; and finally, to discuss the issues, problems, opportunities for solutions. Hopefully, the symposium will result in a better understanding of the research and development and monitoring situation in Alberta with respect to acid deposition, as well as a better understanding of future programs that will provide support for decisions by governments, industry, and environment managers.

2. REGULATIONS

The National Clear Air Act provides ambient air quality objectives for acid-forming emissions, SO_x and NO_x, and other air pollutants. Canada has adopted a three-tier system:

1. The 'maximum desirable level' represents a long-term goal and provides a basis for an anti-degradation policy for unpolluted areas and for the continuing development of control technology.
2. The 'maximum acceptable level' provides for protection against effects on soil, water, vegetation, materials, animals, visibility, personal comfort, and well being. When this level is exceeded, action by a regulatory agency is indicated.
3. The 'maximum tolerable level' represents a level beyond which, because of a diminishing margin of safety, action is required to protect the health of the general population.

The maximum permissible hourly concentrations adopted by the province of Alberta for SO_2 and NO_2 are 0.17 ppm (desirable) and 0.21 ppm (acceptable). It should be noted that Alberta's 1-h standard for

SO_2 is the most stringent in North America. So far, deposition standards for sulphate, nitrate, and hydrogen ions have not been developed. A comparison of wet and dry deposition levels from Alberta with other regions has been published and a need to develop deposition criteria for sulphate, nitrate, and hydrogen ions identified (Sandhu and Blower 1986). A study to develop such guidelines is underway, carried out by the National Research Council of Canada and funded by Alberta, Saskatchewan, Manitoba, British Columbia, Northwest Territories, and Canada. The final report of this study is expected by the end of 1987.

3. OBJECTIVES OF THE PROGRAM

The overall objective of the acid deposition program is to design and implement a research and monitoring program concerning acid-forming emissions and their ecological effects in Alberta. The program will provide scientific information for evaluating and reviewing Alberta's current air quality standards, emission guidelines, and regulatory controls with respect to socio-economic and environmental consequences of atmospheric pollutants and satisfy the concerns of Albertans.

Specific objectives of the departmental program are to:

1. Undertake routine monitoring of air, water, soils, and vegetation to determine short- and long-term trends in environmental quality;
2. Characterize sensitive environmental components and develop methodologies to identify and/or predict environmental deterioration caused by acid-forming substances in Alberta;
3. Characterize, separate, and quantify the contributions of emissions, from local sources and from the medium- and long-range pollutant transport, to environmental effects of acidification;
4. Develop and implement a research program concerning acid-forming emissions and their short- and long-term environmental and health effects;
5. Develop a scientific basis and approach for preventive strategies and environmental protection taking into account socio-economic factors; and

6. Provide support to, and integration of, research, monitoring, and other activities of the Departmental Committee on Acid Deposition, Alberta Government/Industry Acid Deposition Research Program (ADRP), the Western and Northern Canada LRTAP Technical Committee, and other agencies.

As the research and monitoring activities for the LRTAP and government/industry ADRP will be discussed in other representations at this symposium, the remainder of this paper will address details of the acid-forming emissions monitoring program as conducted by Alberta Environment's line divisions, and the research activities undertaken in the northern forested areas of the province. However, the integration of all of these programs will become evident in the following sections.

4. MONITORING PROGRAM

4.1 PRECIPITATION QUALITY

The precipitation quality monitoring program was initiated in 1978 by the Air Quality Control Branch, Pollution Control Division, Alberta Environment. The objective of the program is to monitor the chemical characteristics of rain and snowfall which are representative of different regions in Alberta. The accumulated data base allows the detection of any significant changes in precipitation quality that may occur as a result of industrialization or long-range transport of acid-forming pollutants. The parameters of particular importance are the acidity or pH of precipitation and the sulphate and nitrate deposition rates which are directly related to the acid rain issue.

From 1978 to 1984, there were six provincial precipitation stations in the network. They were located at Beaverlodge, Calgary, Edmonton, Red Deer, Suffield, and Whitecourt. During 1985, three additional stations, at High Level, Cold Lake, and Kananaskis, were put into operation, with the intention of providing additional information about the incoming background chemical contributions to precipitation events.

Besides the nine-station provincial network, the federal government operates five precipitation quality monitoring stations in Alberta under the CANSAP program (Canada Network for Sampling Precipitation).

Their stations are located at Coronation, Edson, Fort McMurray, Lethbridge, and Rocky Mountain House. The monitored data from the federal network and the provincial network supplement each other to increase the coverage in Alberta. The locations of all stations in Alberta are illustrated in Figure 1.

All stations in both networks collect directly comparable monthly samples using automatic rain and snow collectors. Measurements of pH and major ionic concentrations are made on each accumulated monthly sample. The quality of the precipititation is assessed based on the following parameters: (1) acidity from pH; (2) acid-forming emission contributions from sulphate and nitrate concentrations; and (3) dust-related contributions from calcium and magnesium concentrations.

Annual reports summarizing the data from the federal and provincial stations are published by the Air Quality Control Branch, Pollution Control Division, Alberta Environment.

4.2 EXPOSURE STATIONS

The Exposure Station Program consists of 2112 total sulphation and 1276 hydrogen sulphide static exposure stations. These monitors are primarily located in and around urban centres and industrial areas of the province and are used to identify trends. Chemical analysis is done by the Alberta Environmental Centre (Vegreville) and the results are expressed as milligrams SO_3 equivalent per day per 100 square centimetres.

4.3 SOIL MONITORING

Long-term soil acidification monitoring in Alberta, carried out by Soil Protection Branch, Earth Sciences Division, began in September 1981. Monitoring plots were established at eight different areas of the province (Rocky Mountain House, Fort McMurray, Twin Butte, Cold Lake, Esther, High Prairie, Devon, and Bruderheim) between 1981 and 1984 (Figure 2). The objective of this program is to provide an early warning of the potentially adverse effects of atmospheric acid deposition on Alberta's soil resource through the detection of subtle changes in soil properties critical to plant growth. All sites will be resampled once every 4 years. The two principal

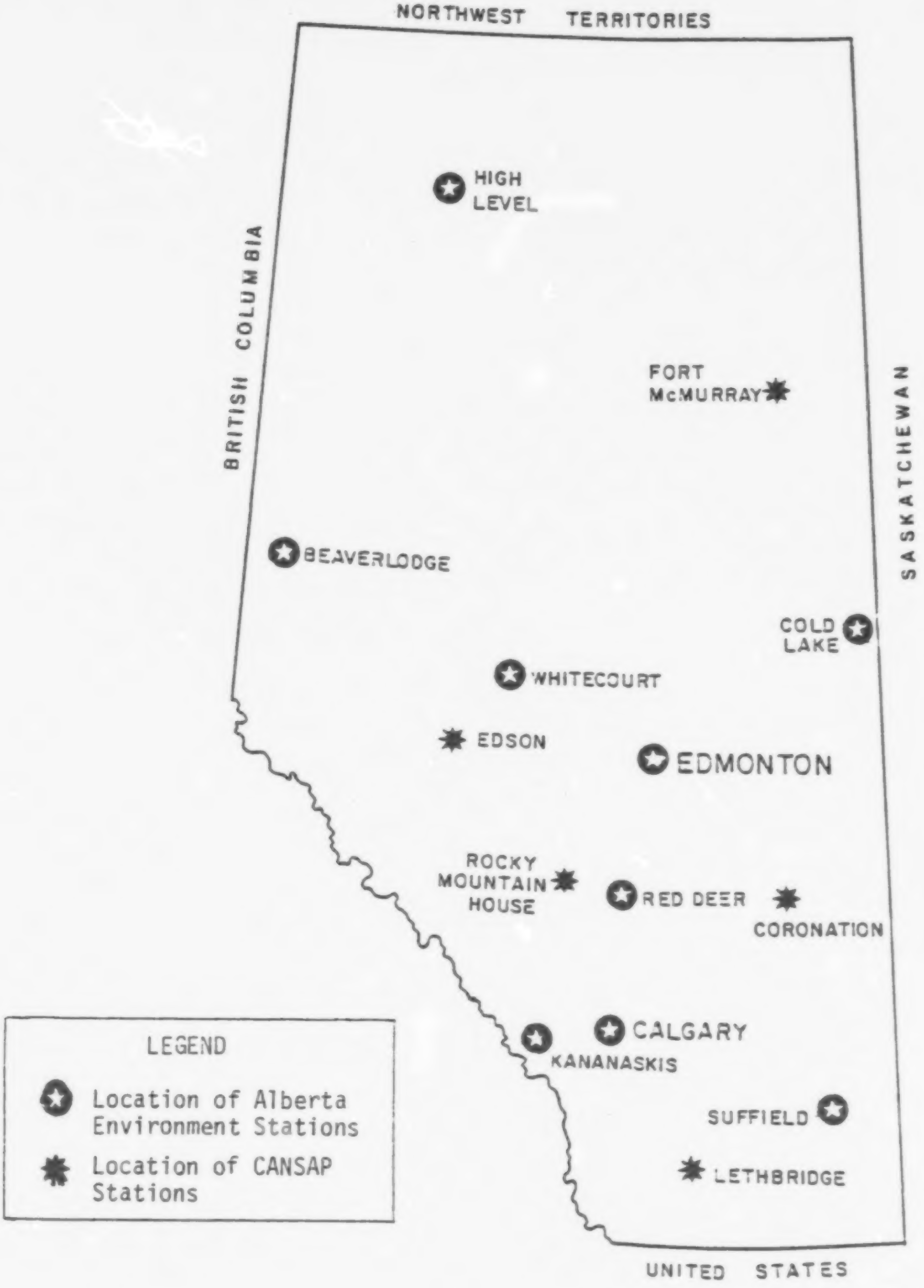
NORTHWEST TERRITORIES
BRITISH COLUMBIA
SASKATCHEWAN
UNITED STATES
HIGH LEVEL
FORT McMURRAY
BEAVERLODGE
COLD LAKE
WHITECOURT
EDSON
EDMONTON
ROCKY MOUNTAIN HOUSE
RED DEER
CORONATION
CALGARY
KANANASKIS
SUFFIELD
LETHBRIDGE
LEGEND
Location of Alberta Environment Stations
Location of CANSAP Stations

Figure 1. Location of precipitation quality monitoring stations in Alberta.

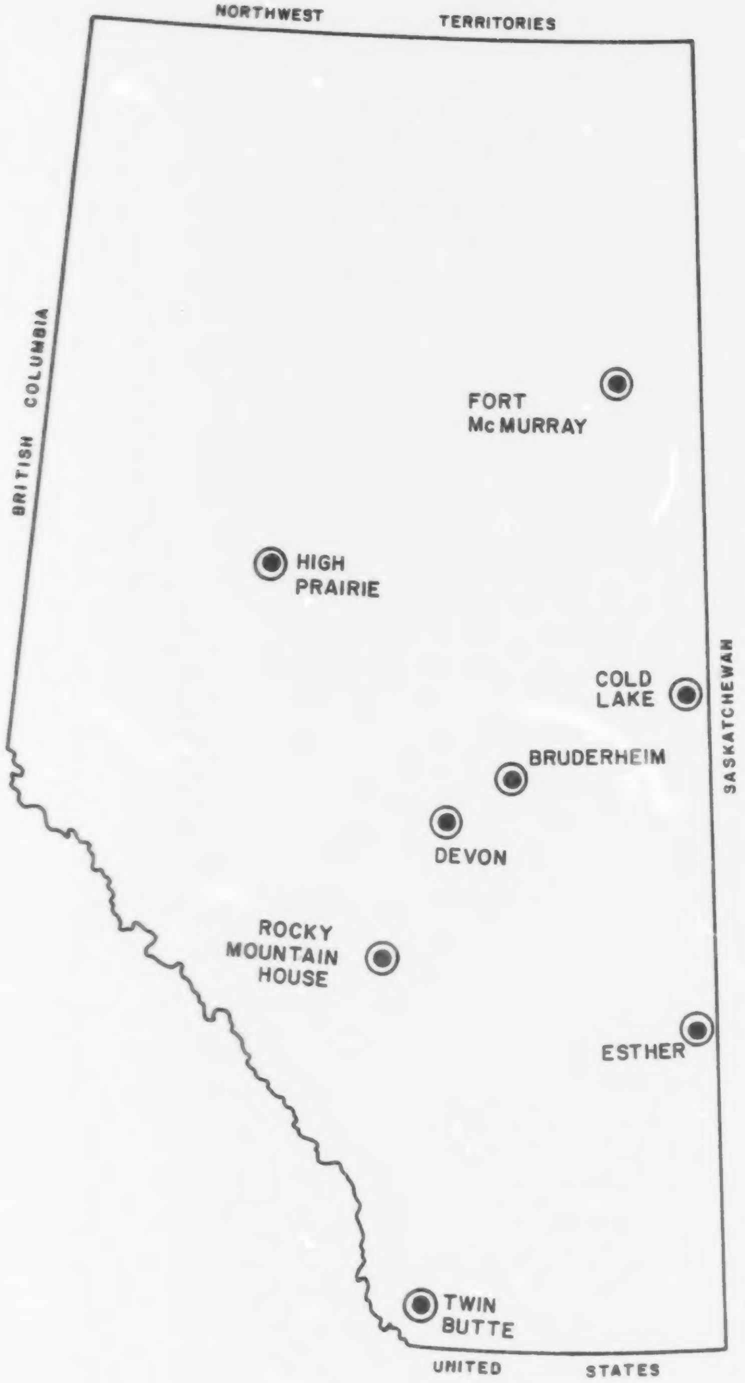
NORTHWEST TERRITORIES
BRITISH COLUMBIA
SASKATCHEWAN
UNITED STATES
FORT McMURRAY
HIGH PRAIRIE
COLD LAKE
BRUDERHEIM
DEVON
ROCKY MOUNTAIN HOUSE
ESTHER
TWIN BUTTE

Figure 2. Long-term soil acidification monitoring sites.

components of the monitoring program are the field sampling and the laboratory analysis.

Soils are the only components routinely monitored at these sites. It is planned to integrate total monitoring efforts (i.e., vegetation, air quality, water quality, and soil) at selected sites in the near future. A concerted effort will be made to combine activities of the relevant provinces and federal agencies.

4.3.1 Field Sampling

Five characteristics were considered important to the selection of monitoring sites.

1. General areas selected for sampling were those identified as areas receiving maximum amounts of acid deposition. These were areas downwind from major sour gas plants, oil sands plants, coal-fired generating plants, and heavy oil extraction plants. Care was taken, however, to locate plots in areas beyond which the localized effects of elemental sulphur dusting could have been an additional source of acid deposition.
2. The most sensitive soils were sampled in each area.
3. Plot areas were located on sites that were as homogeneous as possible with regards to soil characteristics.
4. Undisturbed native soils were selected. Six of the areas are forested and two are on native grassland. Cultivated areas were excluded because of the potential for soil acidification from farm management practices (e.g., fertilizers).
5. Each sampling site was secured, along with a buffer area, by registration with the Land Titles Office. As a precautionary measure, paired plots were established at each site.

The first two characteristics were those considered essential factors for an early warning system. The next two characteristics are important to the detection of subtle changes. The final characteristic is essential to allow for long-term monitoring.

4.3.2 Laboratory Analysis

Due to many different effects of soil acidification, the laboratory analysis program is designed to measure changes in the status of a broad variety of soil chemical properties. Elements chosen for measurement include hydrogen, calcium, magnesium, potassium, sodium, aluminum, iron, manganese, sulphur, nitrogen, carbon, and phosphorus. Soil testing procedures were selected on the basis of being widely accepted and appropriate for measuring the properties of acid soils. Particular care has also been taken to reduce the introduction of variability due to the laboratory analysis program.

4.4 WATER QUALITY MONITORING

The Water Quality Control Branch of the Pollution Control Division maintains a fixed, long-term monitoring network on 11 river locations and 4 central Alberta lakes (Ethel, Baptiste, Nakamun, and Wabamun). All sites are sampled monthly and the samples analyzed for a wide range of chemical constituents and indicators of acidity.

An initial province-wide assessment of the sensitivity of Alberta lakes to acid deposition has been completed. This analysis has identified a number of areas in the northern upland regions, the Canadian Shield area, and the Rocky Mountain national parks which are potentially sensitive. Accordingly, our long-term monitoring network will be expanded to incorporate representative lakes in areas which may be subject to increased atmospheric loading of acid-forming substances. The expansion will occur in 1986 or 1987, subject to budgetary conditions.

5. RESEARCH PROGRAM

5.1 GENERAL

Research to assess long-term environmental impacts of oil sands industrial developments on forested areas has been co-ordinated under the auspices of the Alberta Oil Sands Environmental Research Program (AOSERP). The initial direction of the program (1975 to 1980) was to accumulate baseline information required to quantify and characterize existing environmental conditions. The baseline information could be used subsequently in applied research to assess the impact of industrial development on the environment.

In a review of the research and monitoring activities undertaken during 1975 to 1980, research deficiencies were identified and future research recommended. Specific recommendations were:

1. To characterize and quantify regional and local source emissions to ascertain their relative contribution to environmental acidification;
2. To integrate episodic air quality data with receptor response in order to (1) characterize sensitive environmental ecosystems; and (2) develop methodologies to identify and/or predict measurable short- and long-term effects of acid or acidifying substances on terrestrial and aquatic ecosystems;
3. To develop a scientific basis and approach for preventive strategies and long-term environmental protection/management; and
4. To co-ordinate departmental research on acid deposition with other private and public agencies in Alberta and the rest of Western Canada.

From 1980 to 1985, the program has concentrated on addressing these research deficiencies, especially characterizing and quantifying the ecological effects of acid and acidifying substances. Considerable effort and resources were expended to develop a more thorough understanding of the atmosphere-biosphere interface. Specific projects were geared to the accurate and frequent measurements of pollutant concentration occurrences and their interface with physiological, phenological, and productivity responses in vegetation species. A second major interface, among soil nutrients, microbiological processes, and vegetation, was also being studied. Projects undertaken by the department are listed in the Western Canada LRTAP activities annual reports. A summary report for research and monitoring work carried out in the oil sands area during 1980 to 1985 is in preparation.

Five-year research needs of the Departmental Acid Deposition Program are summarized in Table 1. These are based upon an analysis of: (1) current and ongoing research and monitoring projects on acid deposition

Table 1. Five-year research needs for Alberta Environment's acid deposition research program.

1. Organized evaluation and synthesis of existing information on atmospheric processes, deposition, and receptor responses, as they relate to Alberta.
2. Description of regional (provincial) scale meteorology and atmospheric processes.
3. Characterization of the physics and chemistry of selected Alberta point source plumes with simultaneous ground level measurements.
4. Characterization and quantification of atmospheric deposition of beneficial and deleterious chemical constituents into Alberta ecosystems.
5. Identification and qualitative and quantitative characterization of sensitive receptors and processes related to acid deposition (laboratory and field).
6. Development of numerical methodologies to correlate atmospheric processes and pollutant deposition to effects on total ecosystems (i.e., receptor response) using an integrated approach. This should evolve into predictive capabilities to forecast air-pollutant induced ecosystem impacts.
7. Characterization and quantification of the effects of atmospheric pollutants on human/animal health.
8. Interpretation of program results to determine socio-economic and environmental consequences and mitigation strategies which will assist decision makers in the development of public policy and regulatory guidelines and controls to ensure and maintain environmental quality and human/animal health.

in Alberta developed by Alberta Environment and ADRP; (2) definition and description of Alberta Petroleum Industry Government Environment Committee/ Steering Committee on Acid Gases in the Environment (APIGEC/SCAGE) proposed research plan; and (3) research and monitoring priorities identified by the Western Canada LRTAP Technical Committee.

To address the research needs, a new research program has been designed. This new program, which is described in the following sections, will guide acid deposition research in northern forested areas of Alberta until at least 1991.

5.2 AIR/SOURCE STUDIES

The current and future thrust of research in the atmospheric area is designed to provide scientific information to develop quantitative source-receptor relationships for predicting deposition at short and medium distances from the source (1 to 500 km).

Regional surveys to sample event rainfall and the snowpack for chemical analysis of total pollutant loadings in the oil sands region are needed. Wet deposition, however, is only one of two major mechanisms in the transfer of pollutants from source to receptor. Air pollutants released into the atmosphere are deposited continuously and cumulatively through both dry- and wetfall processes. Methodologies and instrumentation technology developed in earlier years for measuring dry deposition will be implemented.

Present studies include:

1. Measurements of dry deposition;
2. Chemistry of summer and winter precipitation;
3. Mesoscale modelling for establishing deposition patterns;
4. Development of atmospheric target loading for sulphate, nitrate, and hydrogen ions for Alberta and Western Canada; and
5. Acquisition of air quality data for biomonitoring research.

These projects also address the high priority needs identified by Western and Northern Canada LRTAP Technical and Consultative Committees up to 1988.

5.3 ECOSYSTEM/RESPONSE STUDIES

In the 10-year period, 1975 to 1985, the major objectives of the research projects in the ecosystem/response category were to provide baseline information regarding the sensitivity of the oil sands/forested areas to acid deposition, and a preliminary attempt to identify measurable effects of existing acid-forming emissions. Some examples of reports generated during this period are:

1. Baseline condition of jack pine biomonitoring plots in the Athabasca Oil Sands area, 1976-1977 (Addison 1980).
2. Symptomology and threshold levels of air pollutant injury to vegetation, 1979-1980 (Malhotra et al. 1980).
3. Distribution and relative sensitivity to acidification of soils, Sand River area, Alberta (Holowaychuk and Lindsay 1982).
4. Deposition of sulphur and its influence on soils in the AOSERP study area (Nyborg et al. 1985).
5. Establishment and vegetational survey of 16 *Pinus Banksiana*-dominated permanent plots for the Athabasca Oil Sands ecological monitoring project in 1981 (LaRoi and Ostafichuk 1982).
6. Lake acidification potential in the Alberta Oil Sands Environmental Research Program study area (Hesslein 1979).

While the earlier acid deposition research projects provided the needed baseline information, they also demonstrated clearly the high degree of variability in the measurement of ecosystem parameters in these forested systems, and the difficulty with measurement of the effects of low concentrations of pollutants. It has become clear in recent reviews that a new strategy is required for evaluation of acid deposition effects. This strategy will be to develop biomonitoring indices that will be used to monitor effects of low levels of acid-forming emissions over the long term.

Biomonitoring indices selected for impact assessment research will have to be evaluated first for their spatial and temporal variability. Provided that real impact-associated differences can be discerned, the biomonitoring indices developed will be accepted. A further restraint is that the monitoring indices must be feasible for use in long-term programs.

Research activities planned for the 5-year period, 1986 to 1991, include:

1. Evaluation of biomonitoring indices for terrestrial and aquatic systems;
2. Selection of biomonitoring methods and compilation of a data base over a gradient of acid-forming emission (established by the air/source studies); and
3. Investigation of data to develop empirical relationships between emissions and biomonitor response.

5.4 IMPACT MANAGEMENT STUDIES

As well as investigating techniques for monitoring the effects of existing emissions on forested ecosystems, Alberta Environment's acid deposition research program will undertake studies to determine the capacity of the ecosystem to resist detrimental effects. Additional target loading studies will be undertaken to refine and estimate safe levels of deposition to sensitive receptors.

5.5 EMISSIONS CONTROL TECHNOLOGY

Concurrent with the above studies, work will be undertaken on control technologies to reduce emissions at their source. For some time now, the Alberta Environmental Centre has been involved in the assessment and development of a wide range of concepts/processes for the control of acid-forming emissions. Source industries such as gas processing, thermal power, oil sands, gas compressors, and waste incineration have been considered. The use of magnesium oxide to remove sulphur dioxide gas from a sour gas processing plant has been developed and successfully tested at bench-scale. A pilot-scale project is under consideration for funding jointly by Alberta Environment and Environment Canada.

Assuming that feasible control technologies will some day eliminate emissions and emission sources in some areas may be decommissioned over the intervening period, important questions will be: Does the ecosystem recover on its own, and if so, how fast? Where possible, research will be focussed on these questions using field measurements as opportunities present themselves.

5.6 ANIMAL HEALTH

The Alberta Environmental Centre is undertaking a study on the health effects of sulphur gases. The objective is to determine the effects of toxic, or potentially toxic, gases, vapours, particulates, and aerosols on animals and, by extrapolation, on humans. Current studies include the characterization of a 69-L inhalation exposure chamber; commissioning of a new 359-m^2 inhalation toxicology containment facility; studies on the acute toxicity of hydrogen sulphide; in vitro studies and techniques for evaluation of adverse effects of pneumotoxicants; implementation of an inhalation exposure system using 2-m^3 exposure chambers; and field investigations of possible effects on livestock.

6. PROGRAM FRAMEWORK AND MANAGEMENT STRUCTURE

Overall co-ordination of the Departmental Acid Deposition Research Program is provided by the Research Management Division with the advice and support of the Departmental Committee on Acid Deposition (DCAD). Membership on DCAD includes representatives from Pollution Control Division, Standards and Approvals Division, Earth Sciences Division, Alberta Environmental Centre, Research Management Division, and other staff from the department to address specific program needs.

The DCAD addresses all activities, including research and monitoring, and provides liaison between the departmental program and LRTAP and the Government/Industry Acid Deposition programs in order to share technical knowledge and to prevent duplication of efforts.

A new system for approving research projects has been instituted this year by the department. Program Planning Committees have been set up to identify and prioritize research projects to address major environmental issues in the province. In the case of acid deposition, the DCAD, as one of its functions, fills the requirement for an acid deposition research program planning committee.

To ensure that comparable, scientifically valid methodology is used in the departmental program, Alberta Environment has access to the Scientific Advisory Board of Government/Industry ADRP. Where appropriate, departmental project objectives and methodologies will be reviewed by board members and other external scientists and their suggestions incorporated.

7. CONCLUSION

The Departmental Acid Deposition Research Program for Alberta Environment should be viewed as a multi-faceted program, of research, monitoring, and liaison activities, that is designed to address all concerns about the potential effects of acid deposition in the province.

After 10 years of details acid-forming emissions research in forested areas of the province, an important conclusion has been reached: due to the high biological variability and the low acid-forming emission levels, effects research can only be done meaningfully in these areas using long-term monitoring techniques in which biological variability is statistically accounted for.

Parts of the new program which have been referred to in this paper are scheduled to be initiated in fiscal year (FY) 1986/87, with the major start to occur in FY 1987/88. However, before embarking on major new research efforts in the northern forested areas, Alberta Environment felt it was necessary to undertake a detailed review of existing research studies for this area, to make use of the world literature reviews conducted by the Government/Industry ADRP, and to extract the latest information from this symposium. In doing so, FY 1986/87 has been set aside as a review and planning year. To this end, the department has completed the review of oil sands area research, is currently reviewing ADRP literature reviews, and has produced the first draft of a new 5-year plan for research in the oil sands areas.

Protocol has been established and endorsed to integrate the department's program with the Government/Industry ADRP. Efforts to affect this integration are now in progress. In addition, the department has made a formal commitment to continue participation in the Acid Deposition/LRTAP program to 1988, and it is likely that research and monitoring activities will continue well into the 1990s, as long as acid deposition concerns of Albertans persist.

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ACID DEPOSITION IN THE WESTERN UNITED STATES: AN ASSESSMENT

by

P.M. Roth[1]

ABSTRACT

As of the early 1980s, the preponderance of attention given to acid deposition in the United States had been directed toward the eastern and mid-western portions of the country. Although research has been conducted in the western states, no comprehensive effort had been made to review and evaluate available information and to develop general findings. Such a study was recently carried out under the sponsorship of the World Resources Institute.[2] This presentation summarizes the main technical findings, examines concerns, and assesses future implications.

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[1] Consultant in Atmospheric Chemistry, San Anselmo, CA

[2] "The American West's Acid Rain Test", March 1985

1. FINDINGS

A number of mountainous regions in the West[1] are ecologically sensitive, notably the Cascades, the Sierra Nevada, and the Rockies, where many lakes and streams have very low neutralizing capacities. These regions may, in fact, be more sensitive to a given level of acid deposition than areas in the East and Europe that are now experiencing chemical changes and biological damages due to air pollution (although this potentially greater sensitivity has not yet been demonstrated). Greater sensitivities are suspected due to one or more assignable causes:

1. The larger fraction of precipitation that falls as snow in the montane west (and thus, the higher fractional volume of precipitation flushed into streams in the spring and, in turn, the greater potential for temporary acidification);
2. The possibly higher ratio of dry to wet deposition in some sensitive areas of the West, as compared with the East (which results in under-estimation of the total acid stress to ecosystems when only wet precipitation pH is measured);
3. The short growing season at high elevations (which thwarts ecosystem recovery from stresses);
4. The thin soils and steep slopes (which decrease the effective acid-neutralizing capability of the system); and
5. The relatively high abundance of acid-mobilizable trace toxic metals in the soils and lake and stream sediments of the western mountains.

Acid deposition is observed in at least three sensitive montane regions, with annual average pHs of 4.7 to 5.0 and wet sulphate deposition rates of 3 to 9 $kg \cdot ha^{-1} \cdot yr^{-1}$ [and up to 14 $kg \cdot ha^{-1} \cdot yr^{-1}$ (excluding the contributions of sea salts) along the western slopes of the Washington Cascades]. In contrast, in the East, annual average pHs range from 4.1 to 4.5, and wet sulphate deposition rates exceed 20 $kg \cdot ha^{-1} \cdot yr^{-1}$. While it is believed that a deposition rate indicating a threshold for potential damage does not exist, ecological damage has not been observed in eastern North

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[1] 'West' refers to the 11 contiguous states between the Rocky Mountains and the Pacific Ocean.

America or Europe where wet sulphate deposition rates are less than 15 kg · $ha^{-1} \cdot yr^{-1}$. However, total acid deposition rates, for a given wet sulphate deposition rate, may be higher in parts of the West than in the East or Europe, owing to the higher nitrate to sulphate deposition ratios in much of the West. The higher dry to wet ratios in parts of the West may also contribute to higher total deposition rates, although the areas where these ratios are suspected to be higher tend to be other than the mountainous (sensitive) areas.

Emissions of acid precursors in the West are about one-quarter of those east of the Mississippi River. However, they are concentrated in a few major source areas where emissions densities more nearly approach those in the East. In many cases, source areas are situated upwind of sensitive regions. The ratio of SO_2 to NO_x emissions varies widely in the West, from about 3.0 in Arizona to 0.3 in California. Automobiles are the greatest contributors to NO_x emissions in the West, while smelters are the main sources of SO_2 emissions. Electric utilities are the second highest contributors of both species. Given the large spatial variability in types of emissions and emission rates, as well as in location and sensitivity of mountainous regions, acid deposition-related observations and concerns should be viewed as being specific to an area, not as applying to the West as a whole.

Chemical changes attributable to acid deposition have been observed in some areas of the West. These changes include decreasing alkalinity in some western streams and two episodes of temporary lake acidification--one due to an acid pulse from snowmelt and the other to a large volume, low pH storm. Evidence of such changes, however, is limited. This dearth of evidence may be due to a paucity of data or to the fact that such effects are indeed limited (i.e., they occur infrequently or in only a few areas, or are typically small in magnitude). Nevertheless, lake alkalinities in mountainous areas often are quite low (less than 100 $\mu eq \cdot L^{-1}$); introduction of new sources upwind of such areas could lead to temporary or partial acidification.

Biological damages in surface waters due to acid deposition have not been observed in the West. Damage to forests is occurring in the Sierra Nevada and the San Bernardino mountains of California. However, this damage is apparently attributable to the transport of air pollutants from upwind source areas; ozone has been the specific pollutant implicated. There is currently no evidence of forest damage due to acid deposition. Yet, damage through impaction of acid-bearing clouds on forest-covered mountain slopes is a possible concern. Investigations of this potential impact have not been carried out.

2. CONCERNS

Concerns about acid deposition stem from the apparently high level of vulnerability of montane ecosystems; the wet sulphate deposition rates that, at their highest observed levels, approach those in areas where biological damages are now observed; the possibility that total acid deposition rates,for a given wet sulphate deposition rate, are higher in parts of the West than in the East or Europe; and the potential for increased emissions in some areas. Low lake alkalinities and the threat to lakes from acid pulses due to snowmelt add to the concern.

The unknown also breeds concern. The onset of forest damage in Europe was unanticipated; scientists are just beginning to develop an understanding of its causes. They cannot now predict if forest damages due to air pollution will occur more broadly in the West, nor can they estimate the time scale for lake acidification in the face of continuing, albeit low, levels of acid deposition.

3. THE FUTURE

Projections of future emission rates of SO_2 and NO_x in the West, based on 1980 to 1981 data, suggest that, on the average, they will remain relatively constant through the mid-1990s, and then increase. However, significant reductions in emissions have occurred that were not accounted for in the projections, and other new information has become available, placing past estimates of future emissions in question. Unanticipated emissions reductions are attributable to the retirement of older power generation facilities, primarily in southern California; introduction of nuclear power generation and co-generation, a substitute for existing or new conventional power generation; use of natural gas instead of fuel oil (although this trend could reverse with the decline in oil prices); and the actual and anticipated closings of several large smelters. Increases in NO_x emissions from automobiles due to growth have been more or less offset by emissions controls. In California, added control of NO_x emissions from mobile sources is presently under consideration. (The current emissions standard is $0.7\ g \cdot mi^{-1}$; the proposed new standard is $0.4\ g \cdot mi^{-1}$). New construction of large stationary sources is less than projected.

Nevertheless, over the next 20 years, many projects now in the planning stages are anticipated to be completed and operational in Wyoming, Utah, and western Colorado. All in all, available projects for the West for a given year appear to over-estimate emissions regionally.

Current knowledge of acid deposition (emissions, transport, deposition, mechanisms of damage, effects) is inadequate to permit determination of whether or not western ecosystems are threatened or subject to damage by acid inputs. Comprehensive, integrated research and monitoring efforts are needed to provide the relevant information. California's Kapiloff program is a notable example of such a program. Similar programs are needed in the Washington Cascades and the Rockies. The Western Atmospheric Deposition Task Force is in the early stages of planning a program for the Rockies.

THE ROLE OF ACID AND BASE SUBSTANCES IN WET AND DRY DEPOSITION IN WESTERN CANADA

by

Peter W. Summers[1]

ABSTRACT

This paper will consider three aspects of atmospheric deposition in Western Canada, each having important implications for potential ecological effects and, hence, for developing regional air quality management strategies for Western Canada. The three issues are the relative importance of wet and dry deposition, the background deposition levels, and the relationship between SO_4^{2-} concentration and pH.

Only one station (Cree Lake in northern Saskatchewan) has long-term records of both air and precipitation chemistry dating back to July 1982. The wet deposition of SO_4^{2-} shows a marked seasonal variation with a maximum in summer. In contrast, dry deposition varies little through the year. The annual totals for wet and dry deposition of SO_4^{2-} are 3.6 and 1.5 $kg \cdot ha^{-1} yr^{-1}$, respectively.

A first attempt to produce an annual sulphur budget, integrated over the three Prairie Provinces, together with extrapolation of various results from elsewhere, produces a consistent picture in which wet deposition exceeds dry, except near the major sulphur dioxide sources.

Background SO_4^{2-} concentrations in precipitation found in remote areas of the world and along the British Columbia coast are used to estimate the contribution of background to the deposition. Across the Prairies, this background wet deposition of SO_4^{2-} is about 2.0 $kg \cdot ha^{-1} \cdot yr^{-1}$, and at lower elevations along the British Columbia coast, is as high as 10 $kg \cdot ha^{-1} \cdot yr^{-1}$). At Cree Lake, the background is more than half of the observed wet deposition.

The agricultural prairie region presents a special challenge because of the large amounts of soil-generated, windblown material found in the lowest layers of the atmosphere. An analysis of the relationships between H^+, SO_4^{2-}, and Ca^{+} in precipitation in this region, compared to those found in Eastern Canada, indicates that: (1) Ca^{2+} is the main factor controlling pH; (2) much of the SO_4^{2-} originates in soils; and (3) because H^+ is negatively correlated with pH, the validity of the SO_4^{2-} target loading concept in the Prairies needs to be carefully assessed.

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[1] Air Quality and Inter-Environmental Research Branch, Atmospheric Environment Service, Toronto, ON

1. INTRODUCTION

An examination of the precipitation chemistry concentration/deposition maps (e.g., Barrie and Hales 1984) shows a distinct difference in the patterns over Western North America as compared to the east. These differences are due to many factors, including meteorology, topography, land-use, and the strength and distribution of pollution sources. It is not the intent of this paper to review all these factors and how they affect deposition; rather, three aspects of atmospheric deposition in Western Canada, each having important implications for potential ecological effects and, hence, for air quality management, will be considered. The three issues are: the relative importance of wet and dry deposition, the background concentration/deposition levels, and the relationships between precipitation pH and sulphate concentration.

2. DATA SOURCES

The main source of precipitation chemistry data for Western Canada in the past has been the Canadian Network for Sampling Precipitation (CANSAP). A detailed analysis and assessment of the data collected between 1977 and 1980 were made by Barrie and Sirois (1982), and showed problems with monthly sampling especially in Western Canada. Unrealistically high values of calcium (Ca) and magnesium (Mg) were found. A change in sampling protocol instituted in 1980 improved the situation, but some difficulties still existed and, as a result, CANSAP has been phased out in Eastern Canada and will be in Western Canada.

Since 1980, several provincial precipitation chemistry networks have been set up. Also, the Air and Precipitation Network (APN), operated in Eastern Canada since 1979, was expanded to include Cree Lake, Saskatchewan in July 1982.

In 1983, both CANSAP and APN were combined into the new Canadian Air and Precipitation Monitoring Network (CAPMoN). At the present time, the only CAPMoN station making routine air concentration measurements in the west is Cree Lake (although planning for additional sites is underway). Thus, Cree Lake is a key station in the discussion of atmospheric deposition in the west. Because of the scarcity of data in Western Canada, this paper will, therefore, have to make considerable use of relevant results obtained elsewhere.

3. RELATIVE IMPORTANCE OF DRY AND WET DEPOSITION

3.1 GENERAL RESULTS

During the last 20 years, several global sulphur budgets have been produced, eight of which included estimates of the globally integrated wet and dry deposition. There was considerable uncertainty in the estimates, with the range of values for the wet/dry deposition ratio varying between 0.7 and 6.4. Only two studies gave a ratio < 1.0 and the overall average was 1.4. Thus, on a global basis, the 'best estimate' is that 42% of the total sulphur deposition is dry.

Several estimates are available for Eastern North America as summarized in Table 1. It can be seen that the highest percentage of dry deposition occurs in the Eastern United States in the region of high emission source density, where dry deposition exceeds wet. However, in Eastern Canada, the budget estimates and network observations give consistent results with dry $< 30\%$ of the total deposition. The Ontario network average (which includes several sites in the remote regions of northern Ontario) indicates dry to be only 16% of the total deposition.

The relationship between the estimated ratio of wet/dry deposition and emission density for several countries or regions in Europe and North America is shown in **Figure 1**. Although for a given emission there is considerable scatter, all the points fall within the shaded band, indicating a strong correlation between decreasing ratio and increasing emission density.

Using data for the average annual wet and dry deposition at the APN sites from Sirois and Barrie (in press), **Figure 2** was prepared. The distance is measured from the centre of Lake Erie as a reference point. At all sites, wet exceeds the dry deposition of sulphur (expressed as SO_4^{2-}), with both falling off exponentially with increasing distance from the major sulphur dioxide (SO_2) source region. Note the sharp departure from the curve of the wet deposition of SO_4^{2-} at ELA-Kenora, Ontario (ELA) due to the fact

Table 1. Dry deposition of sulphur as a percentage of the total deposition.

Information Source	Dry/Total (%)	Reference[a]
Budget Studies:		
Whole Globe	42	1
Eastern North America	45	2
Eastern United States	57	2
Eastern Canada	29	2
Network Observations		
APN (Eastern Canada)	20	3
APIOS (Ontario)	16	4

[a] (1) Cullis and Hirschler (1980); Summers (1982)
(2) Galloway and Whelpdale (1980)
(3) Sirois and Barrie (in press)
(4) Chan et al. (in press)

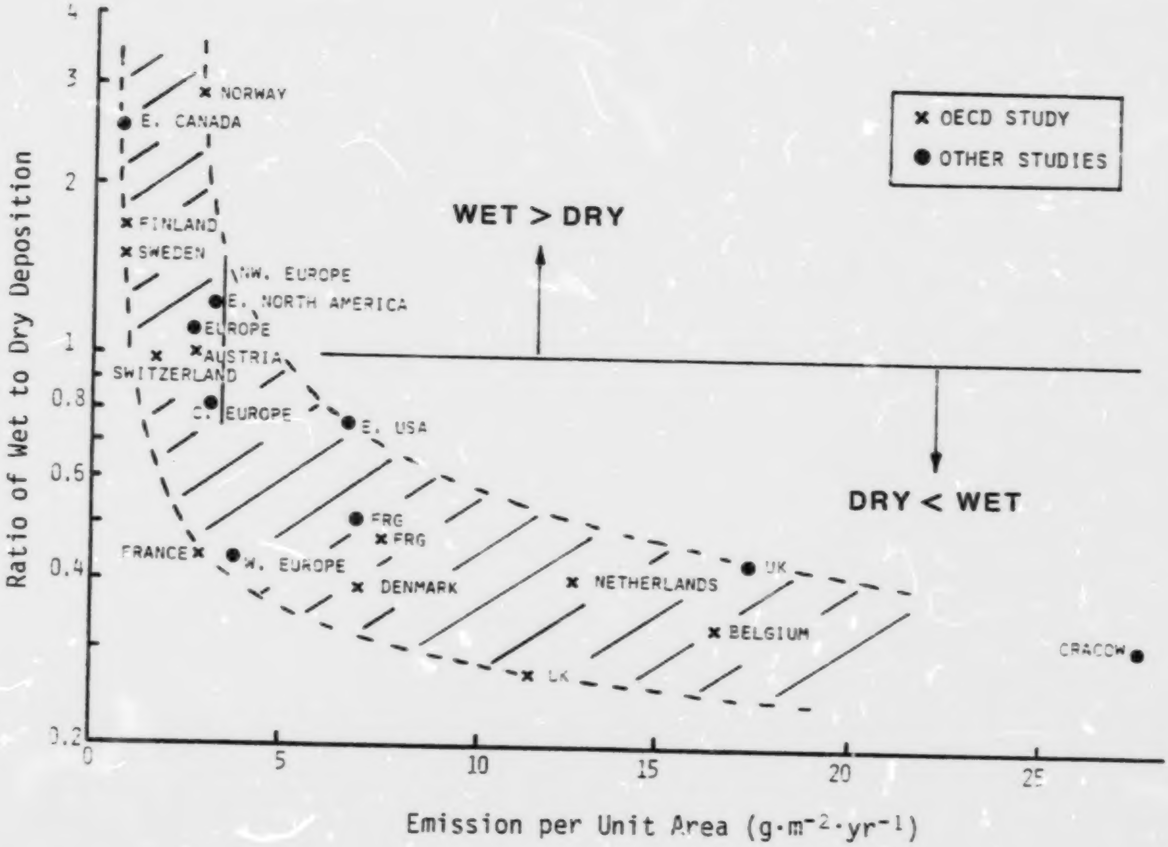

Figure 1. The relative importance of wet and dry deposition of sulphur as a function of emission density, as determined from various regional budget studies in Europe and North America. (Source: Whelpdale and Galloway 1979)

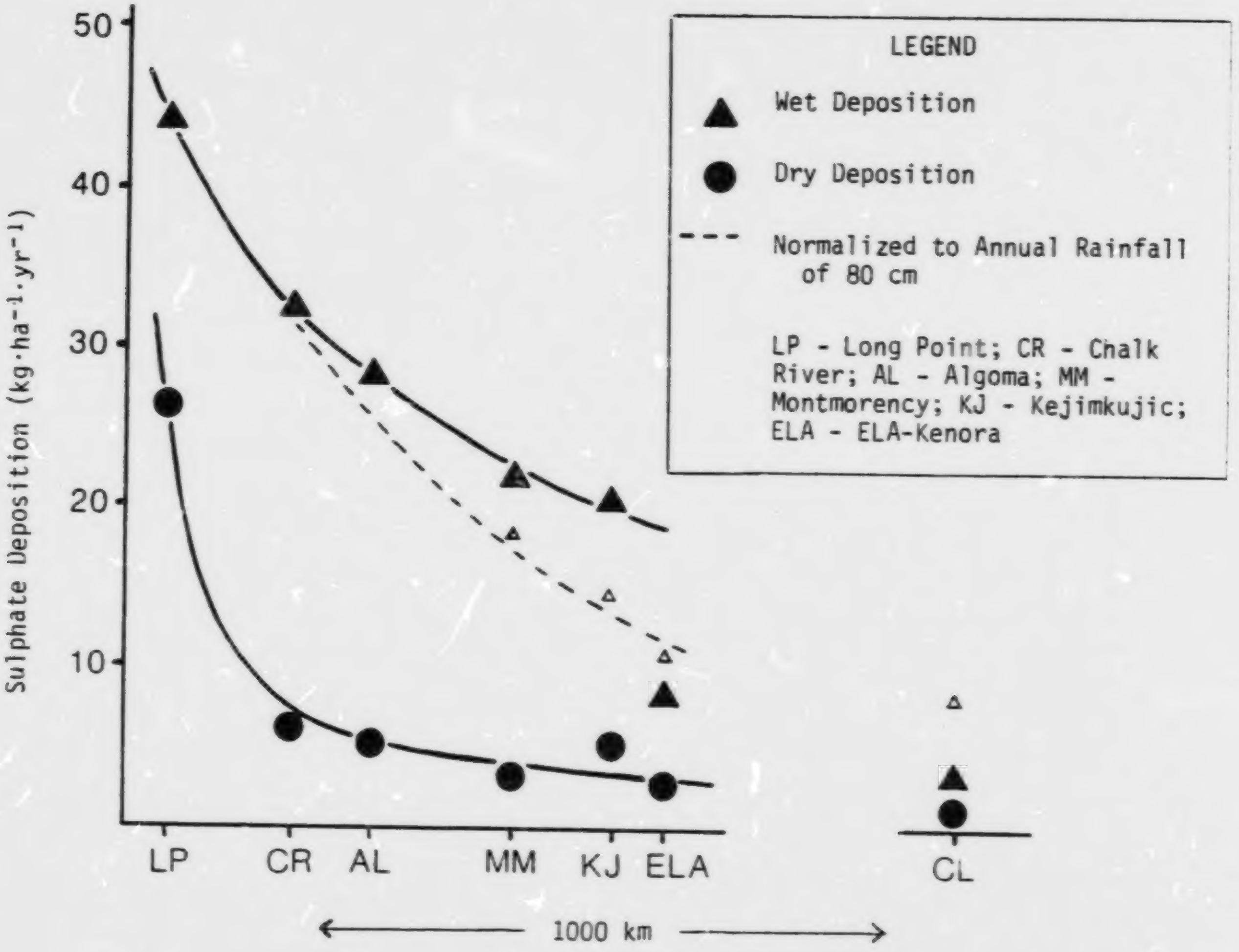

Figure 2. The wet and dry deposition of sulphate at the APN (now CAPMoN) sites in Eastern Canada as a function of distance from the centre of Lake Erie. Also indicated on the right for comparison are the values for Cree Lake. Since there is a wide range of annual precipitation (35 cm to 120 cm) across the region, the wet deposition has been normalized to 80 cm (shown as the dashed line).

that annual rainfall at ELA is approximately half of that at Kejimkujik (KJ), Nova Scotia. In fact, if all the points are normalized to 80 cm rainfall, which is the annual value at Long Point (LP) and Chalk River (CR), then the points lie along the dashed curve.

The general conclusion from all these studies is that, in temperate latitudes where rainfall is greater than 50 $cm \cdot yr^{-1}$, wet sulphur deposition exceeds dry, except within regions of high emission density and close to strong sources of SO_2.

3.2 WESTERN CANADA

The only station in Western Canada with long-term regionally representative measurements of air concentrations is Cree Lake. Using the same technique developed by Sirois and Barrie (1986) for the eastern stations, the dry and wet deposition rates were calculated on a monthly and annual basis.

3.2.1 The Annual Cycle of Concentration (Deposition at Cree Lake)

The monthly values of the major ions measured in precipitation at Cree Lake, averaged over the period July 1982 to December 1984, are shown in **Table 2.** Using the methods developed by Voldner and Sirois (1986) for determining the regional average dry deposition velocities for SO_2 and SO_4^{2-} in combination with the air concentrations measured by filter-pack, the monthly dry deposition was calculated as shown in **Table 3.** The last column gives the total sulphur deposition by adding half of the SO_2 to one-third of the SO_4^{2-} deposition.

The relevant data from Tables 2 and 3 are combined in **Table 4** to show the relative importance of wet and dry deposition of sulphur. The data in Table 4 are shown in **Figure 3.** It can be seen that the dry deposition of sulphur is fairly constant through the year, varying only by just over a factor of 2 between 2.7 and 6.3 $mg \cdot m^{-2} \cdot mo^{-1}$. In contrast, wet sulphur deposition shows a strong annual cycle, with an order of magnitude difference between the highest (24.3 $mg \cdot m^{-2} \cdot mo^{-1}$) and lowest (2.3 $mg \cdot m^{-2} \cdot mo^{-1}$) in May and January, respectively. Dry deposition and wet deposition are

Table 2. Average monthly concentrations of major ions and wet sulphate deposition at Cree Lake (July 1982 to December 1984).

Month	Cl^{-1} ($mg \cdot L^{-1}$)	Ca^{2+} ($mg \cdot L^{-1}$)	NH_4^+ ($mg \cdot L^{-1}$)	Mg^{2+} ($mg \cdot L^{-1}$)	Na^+ ($mg \cdot L^{-1}$)	K^+ ($mg \cdot L^{-1}$)	pH	SO_4^{2-} PCPN (mm)	SO_4^{2-} CONC ($mg \cdot L^{-1}$)	SO_4^{2-} DEP $g \cdot m^{-2}$
Jan	0.608	0.206	0.048	0.024	0.640	0.093	5.28	12.9	0.536	0.0069
Feb	0.322	0.225	0.107	0.033	0.193	0.023	5.59	13.6	0.805	0.0110
Mar	0.531	0.265	0.126	0.044	0.080	0.035	5.29	8.9	0.979	0.0087
Apr	0.376	0.295	0.359	0.043	0.263	0.219	5.02	19.3	1.636	0.0316
May	0.455	0.246	0.202	0.032	0.379	0.157	4.98	41.6	1.754	0.0730
Jun	0.276	0.148	0.109	0.020	0.141	0.072	5.01	58.9	0.775	0.0456
Jul	0.316	0.234	0.130	0.047	0.137	0.091	4.98	49.6	0.939	0.0466
Aug	0.352	0.240	0.088	0.036	0.169	0.045	5.26	64.4	0.884	0.0569
Sep	0.285	0.102	0.084	0.017	0.278	0.043	5.19	16.0	1.048	0.0167
Oct	0.334	0.108	0.050	0.013	0.222	0.023	4.94	30.0	0.912	0.0274
Nov	0.375	0.163	0.066	0.020	0.231	0.063	4.96	30.5	0.681	0.0208
Dec	0.284	0.331	0.076	0.036	0.245	0.102	5.21	15.8	0.715	0.0113
TOTAL								361.5		0.3565

Table 3. Measured mean monthly concentrations (C) of SO_2 and SO_4^{2-} at Cree Lake. Dry deposition (D) per month is calculated as the product of the estimated dry deposition velocity (V_d) and C.

Month	SO_2 C ($\mu g \cdot m^{-3}$)	SO_2 V_d ($cm \cdot s^{-1}$)	SO_2 D ($g \cdot m^{-2} \cdot mo^{-1}$)	SO_4^{2-} C ($\mu g \cdot m^{-3}$)	SO_4^{2-} V_d ($cm \cdot s^{-1}$)	SO_4^{2-} D ($g \cdot m^{-2} \cdot mo^{-1}$)	Total S D ($g \cdot m^{-2} \cdot mo^{-1}$)
Jan	1.347	0.07	0.0025	0.0995	0.18	0.0048	0.0029
Feb	2.199	0.07	0.0037	1.5950	0.19	0.0073	0.0043
Mar	2.118	0.07	0.0040	2.4050	0.21	0.0135	0.0065
Apr	1.015	0.07	0.0018	1.4430	0.22	0.0082	0.0036
May	0.508	0.22	0.0030	1.1840	0.30	0.0095	0.0047
Jun	0.417	0.30	0.0032	0.6760	0.53	0.0093	0.0047
Jul	0.754	0.30	0.0061	0.6720	0.52	0.0094	0.0062
Aug	0.538	0.28	0.0040	0.4030	0.50	0.0054	0.0038
Sep	0.493	0.22	0.0028	0.4160	0.36	0.0039	0.0027
Oct	1.319	0.21	0.0074	0.6550	0.35	0.0061	0.0057
Nov	1.948	0.07	0.0035	0.9790	0.19	0.0048	0.0034
Dec	1.893	0.07	0.0035	0.9180	0.18	0.0044	0.0032

Table 4. The mean monthly values of wet, dry, and total sulphur deposition at Cree Lake, and the relative contribution of dry deposition.

Month	Sulphur Deposition ($g \cdot m^{-2}$)			Ratio W/D	D/T (%)
	Wet (W)	Dry (D)	Total (T)		
Jan	0.0023	0.0029	0.0052	0.79	56
Feb	0.0037	0.0043	0.0080	0.86	54
Mar	0.0029	0.0065	0.0094	0.45	69
Apr	0.0105	0.0036	0.0141	2.92	26
May	0.0243	0.0047	0.0290	5.17	16
Jun	0.0152	0.0047	0.0199	3.23	24
Jul	0.0155	0.0062	0.0217	2.50	29
Aug	0.0189	0.0038	0.0227	4.97	17
Sep	0.0056	0.0027	0.0083	2.07	33
Oct	0.0091	0.0057	0.0148	1.60	39
Nov	0.0069	0.0034	0.0103	2.03	33
Dec	0.0038	0.0032	0.0070	1.19	46

Station: Cree Lake (July 1982 - December 1984)

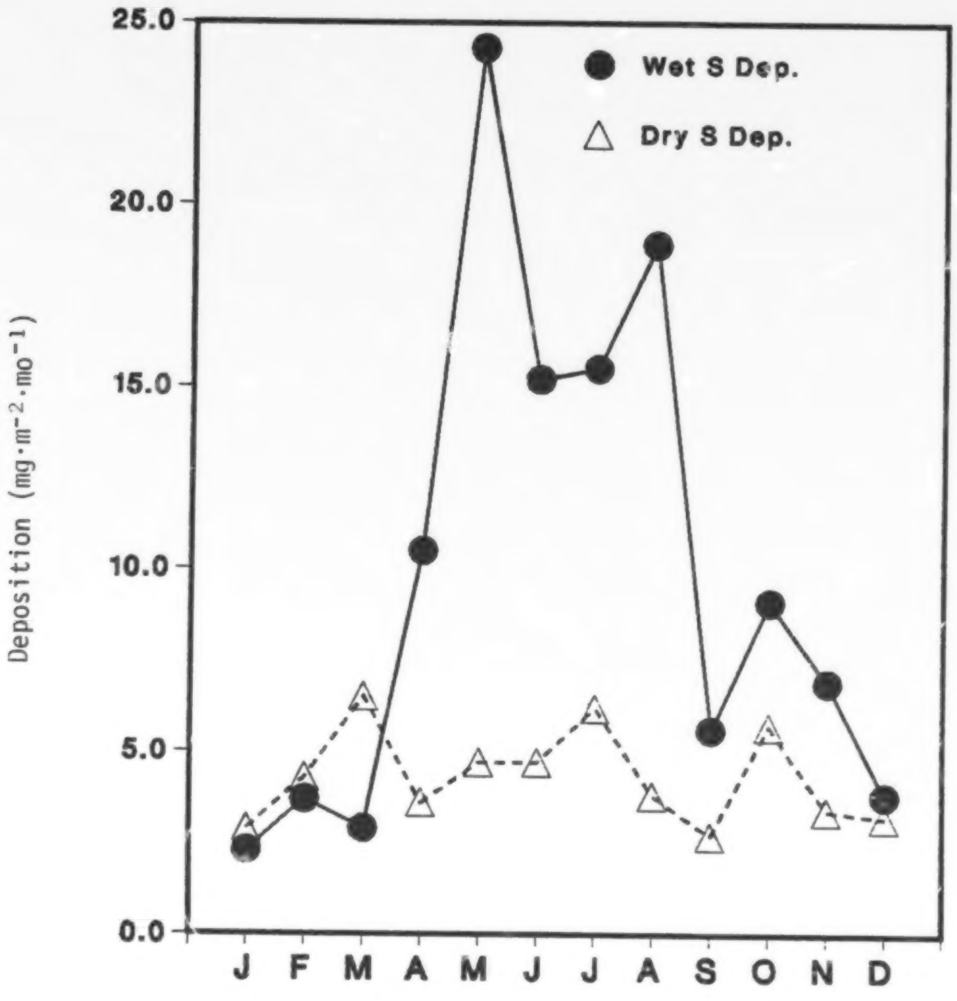

Figure 3. The annual cycle of wet and dry deposition of sulphur (S) at Cree Lake.

approximately equal during the fall and winter seasons, but in the spring and summer, wet exceeds dry by a factor between 3 and 5.

3.2.2 Annual Averages at Cree Lake

The annual average at Cree Lake, determined from the data in Table 4, over the two complete years 1983 and 1984, is shown in Figure 2. Both the dry and wet deposition of SO_4^{-2} are very small compared to the values in Eastern Canada.

A comparison between Cree Lake and ELA-Kenora in northwest Ontario, close to the Manitoba border, is shown in Table 5. Deposition rates at ELA are about twice those at Cree Lake, but the relative importance of wet and dry deposition are about the same. Since both sites are on the Canadian Shield, in regions with similar climate, topography, and vegetation, then, the results can be assumed to be representative of most of the broad area from Manitoba (except the agricultural area in the southwest), across the northern half of Saskatchewan, to northern Alberta. The exceptions would be in the regions surrounding major sources (such as the smelters in Flin Flon and Thompson, Manitoba and the oil sands developments in Fort McMurray, Alberta), where, out to some distance as yet undetermined, dry deposition probably exceeds wet.

3.2.3 An Overall Budget Approach

The previous section dealt only with one location in Western Canada and, as concluded in Section 3.2.2, is probably representative of most of the Canadian Shield area. In the absence of other monitoring data, a broader picture can be obtained by investigating some of the terms in the sulphur budget for the Prairie Provinces. Regional atmospheric budgets are only useful if the residence time of the species of interest is compatible with the distance scale (Rodhe 1978) in such a way that the internal terms, such as emissions, transformation, and removal processes, are larger than the boundary fluxes. Combining the three Prairie Provinces may just meet this criteria. However, because of the large topographical, land-use, and precipitation variability, it is not possible to include British Columbia.

Table 5. Comparison of the annual wet and dry deposition of SO_4^{2-} at Cree Lake and ELA-Kenora.

		Cree Lake	ELA-Kenora
Annual SO_4^{2-} Deposition ($kg \cdot ha^{-1} \cdot yr^{-1}$)	Wet	3.6	7.8
	Dry	1.5	2.7
	Ratio Wet/Dry	2.4	2.9
	Dry/Total (%)	29	26

Table 6 shows the 1980 emissions of SO_2 in each of the Prairie Provinces (Memorandum of Intent 1982), together with the total wet deposition of sulphur obtained by areal integration of the deposition contours for each province. It can be seen that the magnitude of the integrated annual wet deposition is almost equal to that of the anthropogenic emissions. This is not to say that 89% of the wet deposition actually originated from anthropogenic emissions; there are other sources such as agricultural activity and the general background. These will be discussed later. Note that, if all the anthropogenic emissions were deposited uniformly back onto the Prairie Provinces, the average total deposition rate of SO_4^{2-} would be 8.3 $kg.ha^{-1}.yr^{-1}$.

Not included in this deposition estimate is that due to fog or the impingement of low cloud on hillsides. Such deposition can account for a substantial fraction of the total moisture input to high elevation forests. The high concentrations of SO_4^{2-} and NO^{3-} found in fog water leads to extremely low pH values and locally high deposition rates via this mechanism. Results from elsewhere have been discussed and summarized by Barrie and Schemanauer (in press) and Summers et al. (1985). The forested region in the foothills of Alberta, west of the natural gas fields, could receive substantial deposition via this mechanism, but no data are available to estimate the contribution. However, it is likely small in comparison to the total Prairie Province deposition, and is therefore not included in the budget.

In the absence of monitoring data, atmospheric modelling can be used to estimate the wet and dry deposition. This was done by Kociuba et al. (1984), using the AES-LRTAP model (Olson et al. 1979), with the emission and meteorological data for the year 1978. The predicted dry deposition, as a percentage of the total deposition of selected sites, is shown in Figure 4. The data points are too far separated to enable accurate contours to be drawn, but there is some additional information regarding deposition close to the sources. For example, bulk deposition, winter snowpack, and precipitation sampling around the Flin Flon, Manitoba smelter (Franzin et al. 1979) show the influence falling off rapidly with distance.

Table 6. Comparison between the areally integrated wet deposition of sulphur and anthropogenic emissions in the Prairie Provinces.

Provinces	Area	SO_2 Emissions (E)		Wet Depositions (W)	
	(x 10^3 km^2)	(x 10^2 MT)	($g \cdot m^{-2} \cdot yr^{-1}$)	($g \cdot m^{-2} \cdot yr^{-1}$)	W/E
Alberta	661	539	0.41	0.32	0.78
Saskatchewan	652	58	0.04	0.25	6.20
Manitoba	650	490	0.38	0.17	0.45
TOTAL	1963	1087			
AVERAGE			0.28	0.25	0.89

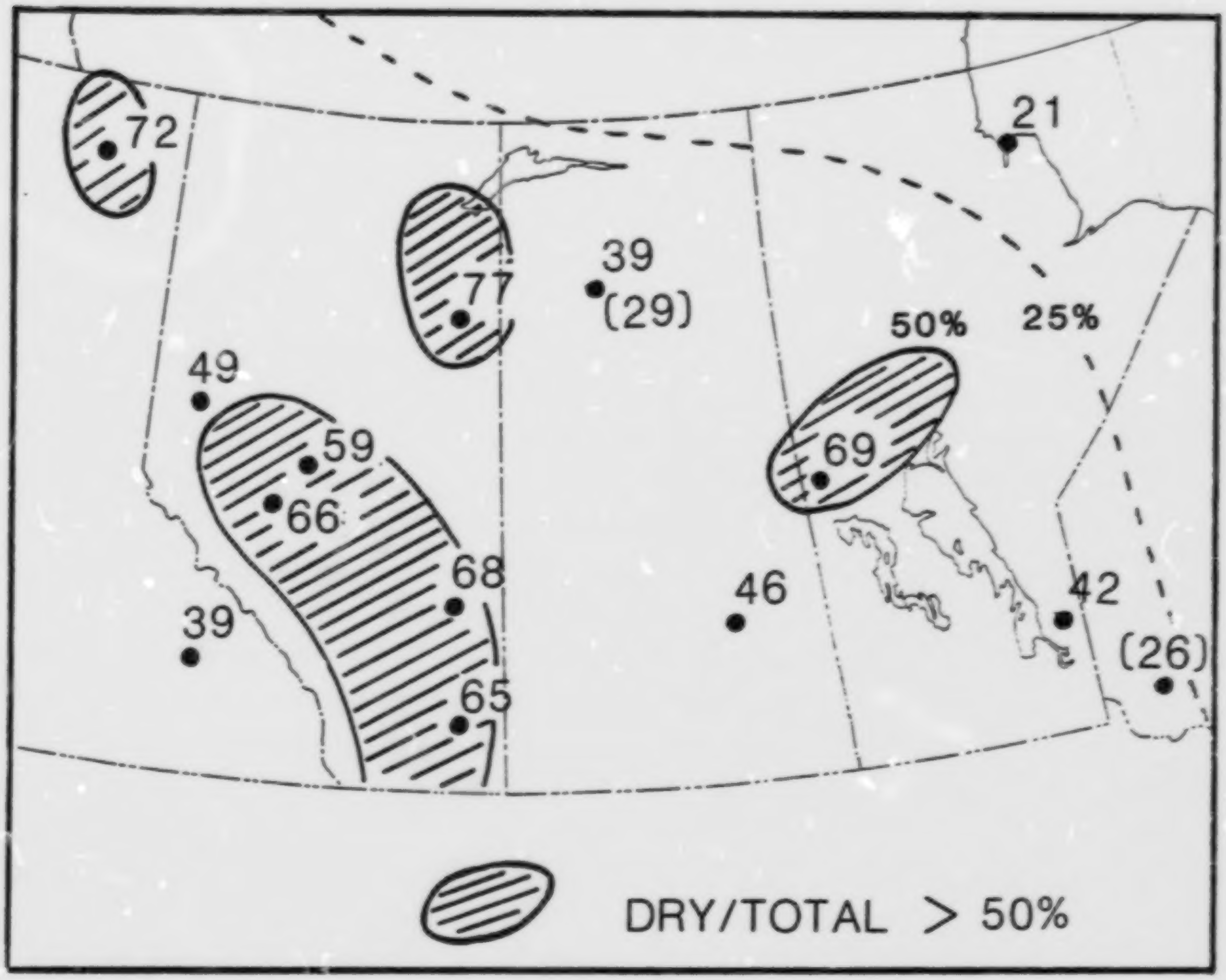
72
77
39
(29)
21
50%
25%
49
59
66
69
68
39
46
42
(26)
65
DRY/TOTAL > 50%

Figure 4. Map of the prairie provinces showing model calculations (Kociuba et al. 1984) of the percentage of total deposition occurring as dry, with the shading indicating approximate areas where dry exceeds wet. Also shown are the percentages ( ) estimated from observations at Cree Lake and ELA-Kenora.

Together with the Thompson, Manitoba smelter, the zone where dry deposition exceeds 50% of the total is approximately as shown. Again, around the oil sands area at Fort McMurray, Alberta, the TRANS model calculations (Weisman et al. 1982) indicate that, in the immediate vicinity of the source, >60% of the deposition is dry, and that dry and wet are approximately equal at the predicted SO_4^{2-} concentration contour value of 0.13 $\mu g\ m^{-3}$. This region is shown in Figure 4 and is consistent with the actual observations at Cree Lake, where dry deposition is estimated to be only 29% of the total. The largest region where dry deposition is >50% is in southern Alberta in the natural gas fields. Figure 4 is thus a self-consistent collage of results from the AES-LRTAP model, the TRANS model, and two observation points. In spite of the uncertainties involved, it appears that wet deposition exceeds dry over all but 15 to 25% of the total area.

The major fluxes of a sulphur budget for the Prairie Provinces are shown schematically in Figure 5. Inputs are shown as solid arrows and outputs as open arrows. Three previously estimated terms are shown--the wet deposition flux (W) and the anthropogenic emissions (E) from Table 6, and the outflow into Eastern Canada (Galloway and Whelpdale 1980). This leaves four unknown terms, i.e., the direct influx (I) of sulphur from British Columbia and the northwestern United States; the contribution from the regional background (B); dry deposition (D); and the contribution to atmospheric sulphur from windblown dust and natural biological activity (N).

Clearly, there is a large number of combinations of these four terms that will 'balance' the sulphur budget. However, other information can be used to give ranges to make estimates of the values of these terms. In the next section, B will be estimated at 13×10^{10} $g.yr^{-1}$. The value of I is difficult to estimate, but again, looking at the flux (10) across the eastern boundary, in relation to the strength and distance of the upwind sources from the boundary, and fluxes across other boundaries in Eastern North America suggests that I is approximately 8×10^{10} $g.yr^{-1}$.

Estimates of the calcium (Ca) emissions, due to windblown dust across Canada (Environmental Applications Group 1982), and summarized by Summers (1982), give a flux of 12.5 $kg.ha^{-1}.yr^{-1}$ across the dry Prairie region, and about one-sixth of this flux over the remaining two-thirds of the

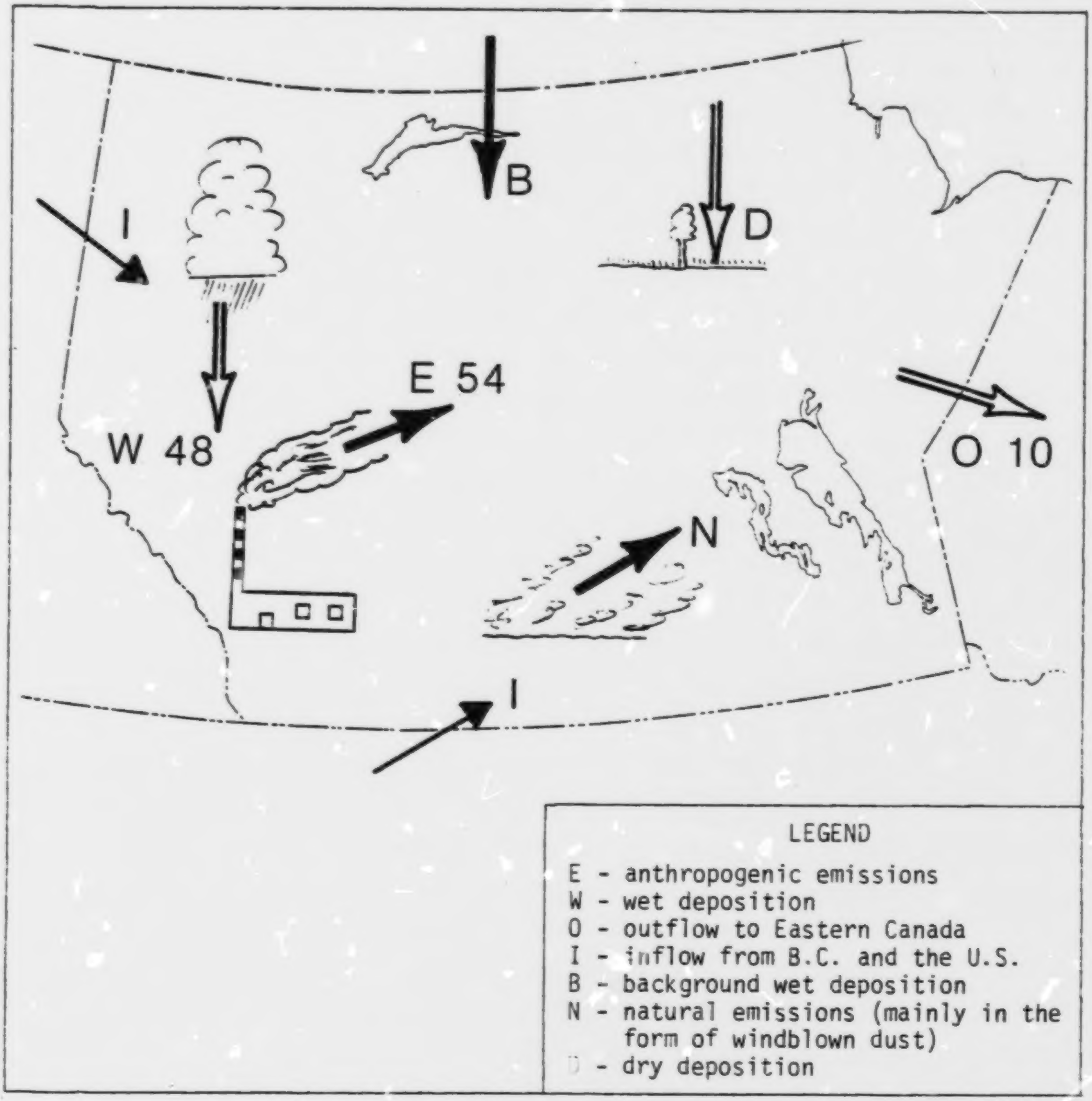
B
I
D
E 54
W 48
O 10
N
I
LEGEND
E - anthropogenic emissions
W - wet deposition
O - outflow to Eastern Canada
I - inflow from B.C. and the U.S.
B - background wet deposition
N - natural emissions (mainly in the form of windblown dust)
D - dry deposition

Figure 5. Schematic representation* of the major fluxes in the annual sulphur budget for the combined prairie provinces (*the geographical placement of the internal fluxes has no implied significance). All units are given as grams X 10^{10} of sulphur per year. The solid arrows indicate inputs to the atmosphere; the open arrows indicate outputs. Previously estimated fluxes are: anthropogenic emissions, E = 54; wet deposition, W = 48; outflow to Eastern Canada, O = 10.

Prairie Provinces. The amount of sulphur in prairie soils has large variations, but typical ranges are given below:

Calcium = 2000 to 9000 ppm
Sulphur = 260 to 380 ppm

Thus, the mass ratio of calcium (Rennie and Ellis 1978) to sulphur (Bettany et al. 1979) varies from 5:1 to 50:1. Without a detailed analysis of the area covered by the various soil types, an integrated value of this ratio cannot be calculated, but, as a first estimate, assumes that in the surface layer of prairie soils the overall average Ca:S ratio is 20:1. Then, using the Ca^{2+} emission estimates, the estimated sulphur flux from windblown dust (N) is 6 x 10 $g.yr^{-1}$ for dry deposition. Although there is a large uncertainty in estimating D this way, this independently estimated value is not inconsistent with Figure 4, or the value obtained from Figure 1 using the average emission density of 0.28 $g.m^{-2}.yr^{-1}$ from Table 6. Thus, as a first approximation, the overall value of dry deposition for the whole Prairie Province region is estimated to be about one-half of the wet deposition.

4. BACKGROUND SULPHATE DEPOSITION AND pH

Until recently, it had often been assumed that the background pH of precipitation would be 5.6, controlled by the equilibrium between the carbon dioxide (CO_2) in the air and the dissolved CO_2 in the precipitation. However, it is now believed that each region of the globe has its own characteristic background precipitation pH, depending on the background levels of acid and base substances in the atmosphere. The latter in turn depend on many factors, the most important of which are: nature of the underlying surface (e.g., desert, ocean, forest, etc.), the climate, and the distance from the 'upwind' anthropogenic sources.

4.1 GENERAL BACKGROUND

There are many ways the natural background can be estimated. On a global basis, at several remote sites operated by the U.S. National Oceanographic and Atmospheric Administration (NOAA), the average concentration of SO_4^{2-} in precipitation is 0.25 $mg \cdot L^{-1}$. In these oceanic areas, there is a lack of base material in the atmosphere and the measured H^+ corresponds to a pH of 4.8. A recent review of natural emissions (Moller 1984) indicates that the natural emissions of acid sulphur precursors are between 50 and 100 $Tg \cdot yr^{-1}$. If this amount were to be deposited uniformly over the whole globe (area 5.1 x 10^8 km^2), then the total deposition would be between 1 and 2 $kg \cdot ha^{-1} \cdot yr^{-1}$. If 58% of this amount is wet (see Table 1), then the average wet deposition of SO_4^{2-} due to natural sulphur emissions would be 1.75 to 3.50 $kg \cdot ha^{-1} \cdot yr^{-1}$.

Measurements of the background acid SO_4^{2-} aerosol in remote oceanic areas are in the range of 0.2 to 1.0 $\mu g \cdot m^{-3}$. In the absence of neutralizing base aerosol in the atmosphere, Charlson and Rodhe (1982) have calculated that the cloud-water pH would range from 4.0 to 5.0; for liquid water content (LWC), in the range 0.25 to 0.50 $g \cdot m^{-3}$ necessary to produce substantial rain awards. Thus, taking a case with 1.0 $\mu g \cdot m^{-3}$ SO_4^{2-} aerosol and LWC of 0.50 $g \cdot m^{-3}$ would give a water concentration of 0.50 $mg \cdot L^{-1}$.

4.2 CANADIAN BACKGROUND LEVELS

North of latitude 60°N, remote from the influence of major man-made pollution sources, the oceans, and Prairie dust, the typical values of the northern continental background for wet deposition can be characterized from Barrie and Hales (1984) as:

Mean annual precipitation pH	= 5.0 to 6.0
Average precipitation SO_4^{2-} concentration	= 0.5 to 1.0 $mg \cdot L^{-1}$
Annual wet SO_4^{2-} deposition	= 1.0 to 3.0 $kg \cdot ha^{-1} \cdot yr^{-1}$

In the winter months, elevated levels of pollution accumulate in the Canadian Arctic (Barrie in press) due to transport from mid-latitude sources leading to typical air concentrations as follows:

SO_4^{2-} = 0.8 to 2.1 $\mu g \cdot m^{-3}$

SO_2 = 1.0 to 2.4 $\mu g \cdot m^{-3}$

NO^{3-} = 0.1 to 0.6 $\mu g \cdot m^{-3}$

Thus, in the absence of neutralizing basic species in the atmosphere, the acidity of snow forming in Western and Northern Canada, east of the Rockies, would be expected to range from 5 to 20 $\mu eq \cdot L^{-1}$ (i.e., pH 4.8 to 5.3).

A recently completed study of background SO_4^{2-} in precipitation along the British Columbia coast arriving from the Pacific Ocean (Atmospheric Environmental Service 1986) shows values in the range 6 to 10 $\mu eq \cdot L^{-1}$, or 0.3 to 0.5 $\mu g \cdot L^{-1}$.

Concentration values are observed to be more continuous in space than deposition because the latter includes the more highly variable precipitation amount. Thus, taking the typical range of background concentrations noted above, Table 7 translates them into a deposition rate for a range of annual rainfall.

4.3 BACKGROUND DEPOSITION IN WESTERN CANADA

4.3.1 Cree Lake

The annual precipitation at Cree Lake is approximately 40 cm. Thus, for a typical background concentration for SO_4^{2-} or 0.5 $mg \cdot L^{-1}$, the background wet deposition from Table 7 would be 2.0 $kg \cdot ha^{-1} \cdot yr^{-1}$. This is about 57% of the wet deposition (see Table 5) or 40% of the total deposition.

4.3.2 The Prairie Provinces

The average rainfall across the Prairie Provinces is about 40 cm, giving a background deposition rate the same as for Cree Lake, i.e., 2.0 $kg \cdot ha^{-1} \cdot yr^{-1}$. Multiplying this value by the total area would give a total areally integrated annual SO_4^{2-} background deposition of 13 x 10^{10} $g \cdot yr^{-1}$ over the Prairie Provinces. This is 27% of the total wet deposition indicated in Figure 5.

4.3.3 British Columbia

The highly variable precipitation in British Columbia means that the point deposition is highly variable. Further, the discontinuities in the

Table 7. The estimated background deposition of SO_4^{2-} as a function of annual rainfall amount for a range of background SO_4 concentrations (C).

Annual Rainfall (cm)	SO_4^{2-} Concentration (C)		
	0.25 $mg \cdot L^{-1}$	0.50 $mg \cdot L^{-1}$	1.00 $mg \cdot L^{-1}$
	SO_4^{2-} Deposition ($kg \cdot ha^{-1} \cdot yr^{-1}$)		
30	0.75	1.5	3.0
50	1.25	2.5	5.0
100	2.50	5.0	10.0
200	5.00	10.0	20.0

rainfall pattern, imposed by the topography, make it impossible with the sparce precipitation chemistry data to estimate an integrated provincial deposition.

Along the west coast near sea level, where rainfall is of the order of 100 to 200 cm per year, SO_4^{2-} deposition is probably in the range 5.0 to 10.0 $kg.ha^{-1}.yr^{-1}$.

5.0 IONIC RELATIONSHIPS

The relationships between the major ions in precipitation are of interest from several points of view. First, the spatial and temporal variations of these relationships, on comparison to the precursor emissions, are clearly useful in understanding the atmospheric chemistry processes. Second, when deposition is considered as the input to the ecosystem, the relationships between variables, such as pH, SO_4^{2-}, NO^{3-}, NH_4, and Ca^{2+}, are very important in the way they drive the chemistry of the soil/water system.

A full analysis of the relationships for Western Canada will not be presented here, but two important aspects will be treated in a preliminary way.

5.1 RELATIONSHIP BETWEEN ACIDITY AND SULPHATE

The relationships between H^+ and the major ions for precipitation in the Eastern United States for the period 1980 to 1981 were presented by Gorham et al. (1984). They found the highest correlation was between H^+ and SO_4^{2-}. A similar analysis was done for CANSAP data for Eastern and Western Canada using a line from Lake Superior to James Bay to Ungava as the dividing line. The results are shown in Table 8. The relationships in the Eastern United States and Eastern Canada, both dominated by SO_4^{2-} of anthropogenic origin, are similar. However, in Western (and Central) Canada, there is essentially no correlation between H^+ and SO_4^{2-} concentrations.

5.2 RELATIONSHIP BETWEEN SULPHATE AND CALCIUM

To investigate the lack of correlation between H^+ and SO_4^{2-} in the west, the relationship was expanded to include the major cation in

Table 8. Correlation between pH and precipitation sulphate concentration ($\mu eq \cdot L^{-1}$) in three regions of North America.

Region	Regression Equation	r^2
Eastern United States[a]	$H^+ = 1.17\ [SO_4^{2-}] - 19.1$	0.85
Eastern Canada[b]	$H^+ = 1.05\ [SO_4^{2-}] - 13.9$	0.81
Western Canada[b]	$H^+ = 16.3 - 0.45\ [SO_4^{2-}]$	0.05

[a] Gorham et al. (1984)
[b] CANSAP data

precipitation, i.e., calcium. The role of alkaline materials in precipitation chemistry has been reviewed by Gatz et al. (1985). The results for the annual average values in 1981 are shown in Figure 6; other years show a similar relationship. Each data point represents one site in the CANSAP network, plotted as shown for the appropriate mean annual value of the Ca^{2+} and SO_4^{2-} concentrations on the ordinate and abscissa, respectively. Not shown is the pH associated with each point, but they do form a consistent pattern represented by the lines of equal pH as drawn on the figure. Apart from three exceptions, the data points fall into two well-defined groupings. The Eastern Canadian sites (solid triangles) show a small range of Ca^{2+} concentrations and a wide range of SO_4^{2-} concentrations, all falling within a narrow band delineated by the dashed lines, with the pH decreasing as SO_4^{2-} increases, consistent with the results in Table 8. In contrast, the Western Canada data (solid circles) show a small range of SO_4^{2-} concentrations and a very wide range of Ca^{2+} concentrations. The data points again lie within a narrow band, as indicated by the dotted lines, but now the pH increases as SO_4^{2-} increases, due to the overwhelming control of the Ca^{2+} concentrations consistent with the regression equation in Table 8.

Figure 6 contains a large amount of information of significance to the acid rain issue in Western Canada. Some important conclusions that can be drawn are as follows:

1. The fact that the lines of equal pH, based on the observations, have a slope of 1.0 indicates that Ca^{2+} and SO_4^{2-} are the major controlling ions found in the precipitation.
2. The fact that the pH = 5.6 does not go through the origin (to be expected if SO_4^{2-} and Ca^{2+} were exactly in balance) shows that other ions (such as Mg^{+} and NO^{3-}) are also important.
3. The lowest annual average SO_4^{2-} concentrations observed in Canada are between 6 and 8 mol L^{-1}, consistent with the background values discussed in Section 4.2.
4. Expressing the amount of sulphur in Prairie soils as SO_4^{2-} gives a Ca^{2+}:SO_4^{2-} ratio of 7:1. The line expressing this ratio is shown in Figure 6 and is almost parallel to the

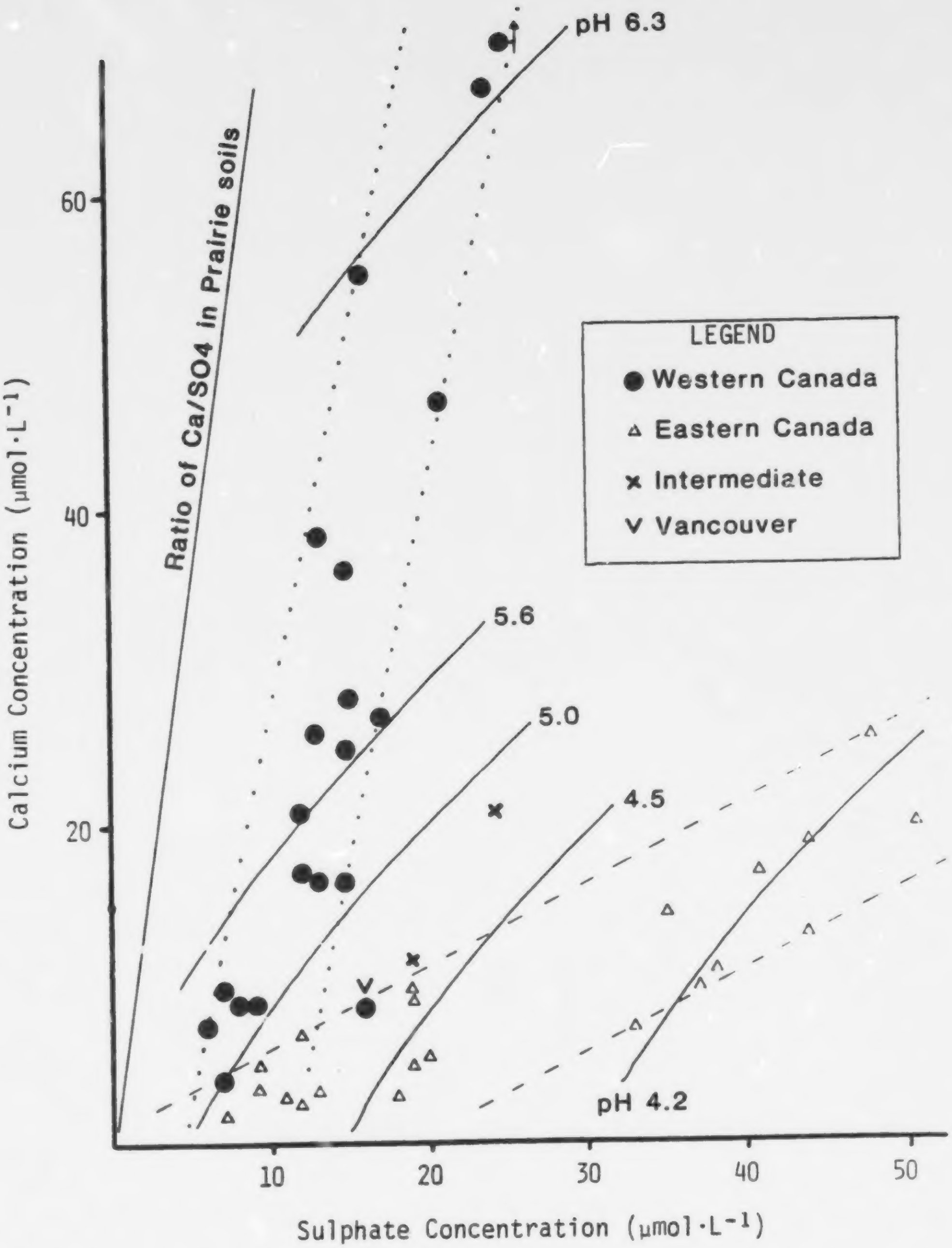

Figure 6. The relationship between the annual average SO_4^{2-}-concentration, Ca^{2+} concentration, and pH of precipitation for the CANSAP stations in 1981. Also shown is the typical ratio of Ca^{2+}/SO_4^{2-} in prairie soils.

relationship found in western precipitation. The difference in slopes indicates a slight excess of SO_4^{2-} above the background, presumably of anthropogenic origin. In contrast, in Eastern Canada, most of the SO_4^{2-} is not associated with soil consistent with the large anthropogenic component.

5.3 IONIC RELATIONSHIPS AND TARGET LOADING FOR WESTERN CANADA

The concept of a target loading for wet deposition of SO_4^{2-} was developed in Scandinavia and its application extended to Eastern Canada. It was based on the observation that ecological damage to lakes (except for the most sensitive) does not occur with annual SO_4^{2-} wet deposition rates below some value. This value became known as the 'target' loading on the basis that, if protection or recovery of lakes was to be provided, then, controls of SO_2 emissions would be needed to maintain, or bring, the wet SO_4^{2-} deposition below this 'target' value.

Since many of the effects detected in lakes were related to pH rather than SO_4^{2-} concentration, implicit in the target loading concept is a high correlation between pH and SO_4^{2-}, in both the lake system and the precipitation input. This is true for regions of high anthropogenic sulphur input in Eastern North America (see Table 8) and also in Europe. It must also be remembered that pH is really a concentration of H^+ ions, and a SO_4^{2-} loading is a concentration multiplied by the rainfall amount. Thus, the interchangeability of pH, SO_4^{2-} concentration, and SO_4^{2-} loading, in describing sensitivity or observed effects, are used by Gorham et al. (1984), is only valid in a region of relatively uniform rainfall.

It is obvious from the above that, as soon as one considers the much drier climate in the Prairie Provinces and the different relationship between pH and SO_4^{2-}, the concept of a target loading must be applied with caution, if at all. A study has been initiated by the Western LRTAP Consultative Committee (WLCC) to examine this question in detail.

5.4 A SOIL SULPHATE CORRECTION

As a matter of course now, most precipitation SO_4^{2-} values are corrected for a sea-salt contribution before interpreting the data in terms of the acid sulphate content. This can be done because there is a nearly constant ratio of chemicals in seawater. Thus, using one such as sodium (Na), that does not get into the atmosphere by another route, the known ratio of Na to SO_4^{2-} in seawater can be used to subtract the fraction of SO_4^{2-} found in precipitation due to the seawater source. The relationships in Figure 6 suggest that, for the Prairies, a soil-sulphate correction might be appropriate. This would be feasible if the ratio of SO_4^{2-} to Ca^{2+} or Mg^{2+} was constant. Although, averaged over large regions, the ratio may be fairly stable, the Ca^{2+} and Mg^{2+} found in precipitation are usually of quite local origin, due to the short residence of these species compared to acid SO_4^{2-} aerosols. Hence, the necessary correction factor would have high spatial variability. However, in spite of these difficulties, the possibilities of developing such a correction factor may be worth pursuing if the true impact of anthropogenic SO_4^{2-} is to be better understood.

6. SUMMARY AND RECOMMENDATIONS

6.1 IMPORTANT ISSUES IN WESTERN CANADA

From the overview of atmospheric deposition in Western Canada, several important issues, that are different from those in Eastern Canada, have emerged that clearly must be considered in developing an emissions control strategy to protect the west from the impact of acid deposition. These are as follows (not necessarily listed in order of importance):

1. Over most of Western Canada, background wet deposition is a large fraction of the total.
2. Alkaline dust plays a major role in the atmospheric chemistry of the Prairie agricultural regions.
3. Mainly as a result of (2), the relationships between pH and acid and base concentrations in precipitation are very different in the west compared to the east.
4. The implication of (3) could have a profound influence on the applicability, or otherwise, of the target loading concept to Western Canada.

5. Dry deposition plays an important role in Western Canada, although, because of a lack of appropriate monitoring data, there is a large uncertainty in its absolute magnitude. However, using various methods, the dry deposition of sulphur is estimated to be greater than wet near the major sources but, averaged over the whole of the Prairie Provinces, is about half of the wet input.
6. There does not appear to be a large-scale (of the order of 1000 km) pollution transport problem in Western Canada; rather, transport and deposition on the regional scale (< 300 km) is the current issue to be addressed.

6.2 SOME MONITORING AND RESEARCH NEEDS IN WESTERN CANADA

Monitoring and research needs are continually being addressed and updated by the western provinces and the WLCC and will not be comprehensively discussed here. This paper does indicate two areas where more attention would be useful, not only for improving scientific understanding of the issues, but also for providing relevant input to policy development:

1. CAPMoN-type stations, providing high quality daily sampling of air and precipitation, are required at a few carefully selected sites in addition to the one at Cree Lake. The goal would be to more firmly establish the chemical climatology of Western Canada, the relationships between the ionic components of wet deposition, and the relative importance of wet and dry deposition. First priority should be given to sites in the Prairie agricultural region and the British Columbia coast.
2. Refinement of the sulphur budget for the Prairies should be continued in order to put upper and lower bounds on, and assess the relative importance of, the various input and output fluxes. Such an approach is useful in putting site-specific monitoring or research projects in the broader context, and also in guiding the direction of future monitoring and research to focus on the terms having the largest uncertainty or that are most crucial in the budget.

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AN INVENTORY AND FORECAST OF ACID-FORMING EMISSIONS IN ALBERTA

by

D.G. Colley[1] and D.J. Picard[1]

ABSTRACT

Acid rain precursor emissions from Alberta sources are analyzed and based on two provincial growth scenarios (high growth and low growth), and forecasts of emissions to the year 2000 are presented.

The growth scenarios developed consider natural gas and conventional crude oil production, oil sands development, electric energy generation, and other industry groups, such as pulp and paper, fertilizer, refineries, and manufacturing operations. In addition, they consider, where appropriate, residential and commercial developments and the transportation sector.

After the growth scenarios are developed, each sector is examined to determine its potential to emit sulphur dioxide or oxides of nitrogen to the atmosphere. The atmospheric emissions for each sector and the province are forecast with the application of present, best practicable, and best available technology for either by-product recovery or emission control.

The forecasts to the year 2000 are examined and the consequences of applying the various levels of technology are discussed.

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[1] Western Research, Division of Bow Valley Resource Services Ltd., Calgary, AB

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This paper is based on two studies sponsored by Research Management Division, Alberta Environment, in 1982 and 1983 to forecast sulphur dioxide and oxides of nitrogen emissions for Alberta. Permission to summarize these two reports in this document is gratefully acknowledged. Copies of the detailed reports may be obtained by contacting Research Management Division at 14 Floor, 10405 Jasper Avenue, Edmonton, AB, T5J 3N4.

1. INTRODUCTION

Forecasts of sulphur dioxide and oxides of nitrogen emissions are essential information for developing air quality management strategies and for assessing the need for research, development, and implementation of emission control or by-product recovery systems. Sulphur dioxide emissions are associated with oil and gas production, electric power production, oil sands, and other industrial operations. Oxides of nitrogen are also produced by these same sources but, in addition, substantial contributions are attributable to transportation components, including passenger cars, commercial vehicles, and railway locomotives and, to a lesser extent, residential and commercial sources.

To examine the impact of various growth rates, two growth forecasts were developed for the province. The higher growth forecast (Scenario A) takes an optimistic view of industrial development, the demand for natural gas, vehicle ownership and usage, and population growth. To look at the downside, less optimistic growth forecasts (Scenario B) for each component were also developed.

After the two growth forecasts were developed, each source was examined to determine its potential for emissions of both sulphur and oxides of nitrogen. Subsequent to this assessment process, present, best practicable, and best available by-product recovery or emission control technologies were defined and applied to develop the emission forecasts. Advanced control technologies were defined and applied at the discretion of the authors and not based on industry or government recommendations, nor on studies that have demonstrated environmental need or economic feasibility.

The results of the studies (Colley and Poon 1982; Colley et al. 1984) are two (growth) by three (technology) matrices of emission potential for both sulphur dioxide and oxides of nitrogen in the province. Strategies for air quality managment and technology research and development can be formulated through the use of the forecasts.

2. PROVINCIAL GROWTH FORECASTS

In the development of the Alberta growth profiles, consideration is given to natural gas and conventional crude oil production; mining and in-situ oil sands development; electric energy generation; other industrial developments such as petrochemical, refinery, fertilizer, and pulp and paper; and other manufacturing operations, residential and commercial developments, and the transportation sector.

Reference is made to relevant industry and government projections of energy demand and population growth, and to proposals for new industrial projects.

The growth profiles for the sulphur dioxide and oxides of nitrogen emission forecasts are identical. The basic components describing the two growth scenarios are:

1. Population: Populations of 3.8 and 3.0 million are forecast by the year 2000 for the two growth scenarios, as compared to 2.2 million in 1982. This corresponds to annual growth rates of 2.9 and 1.8%, respectively.
2. Transportation: Passenger car and commercial vehicle growth rates are shown in Figure 1. For Scenario A, growth rates of 3.8 and 4.0% per annum are forecast, while for Scenario B growth rates of 2.6 and 3%, respectively, are indicated. For both growth scenarios, rail locomotive fuel oil consumption is projected to increase at a rate of 3%.
3. Electrical energy generation: Total energy requirements and the portions supplied by gas-fired and coal-fired generating stations are shown in Figure 2. Total energy requirements are expected to increase by 190 and 140% for Scenarios A and B, respectively.
4. Oil sands: Production of synthetic crude oil is forecast to increase from present levels of about 34 000 $m^3.d^{-1}$ to 84 000 $m^3.d^{-1}$ by 2000 for Scenario A, while no significant increases are forecast to occur for Scenario B. These are shown in Figure 3.
5. Other industries: Other industrial growth is expected to increase modestly throughout the forecast period and, in terms of natural gas consumption, the growth rate is estimated to be 4.6% per annum for both scenarios.

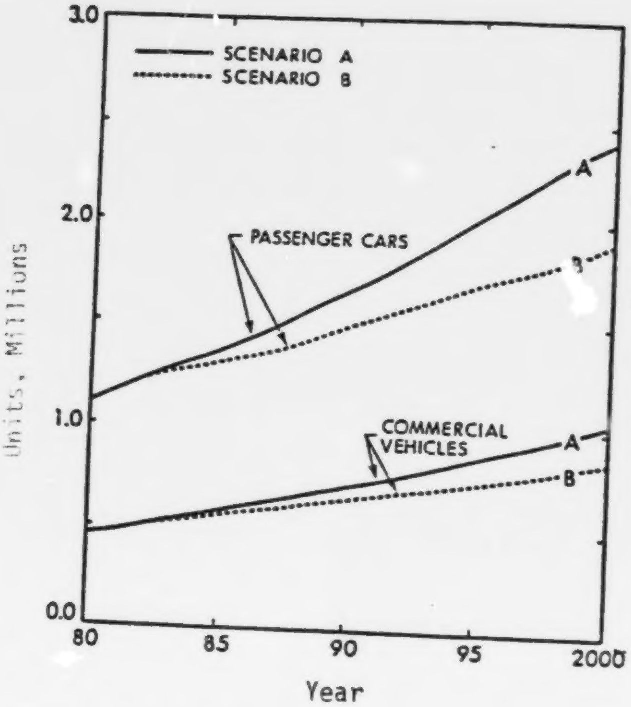

Figure 1. Transportation growth.

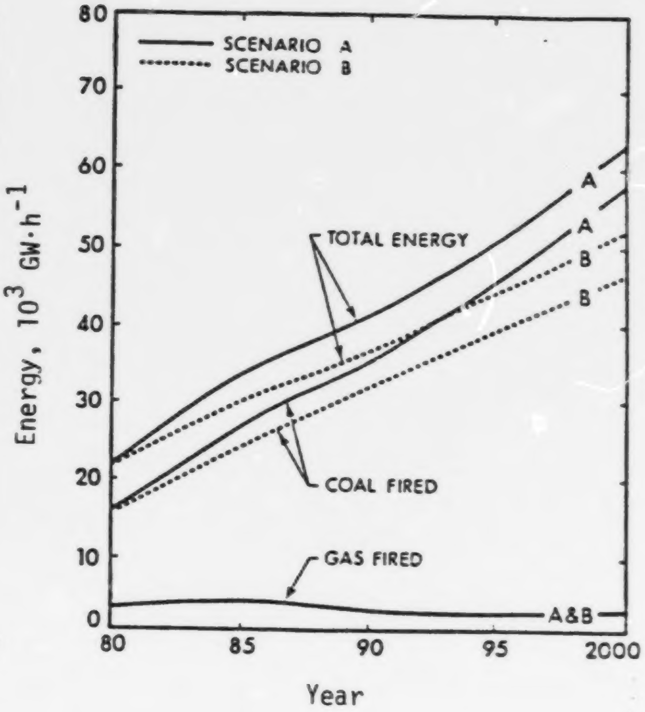

Figure 2. Electric energy generation.

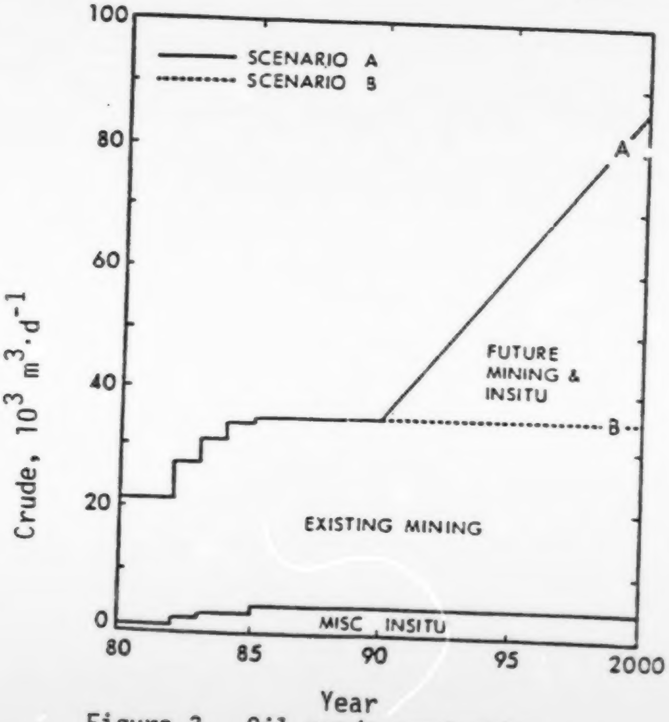

Figure 3. Oil sands production.

6. Natural gas: A demand forecast for total marketable gas delivered from Alberta sources was developed after examination of Alberta's requirements, other Canadian requirements in traditional market areas, expanded eastern markets, existing export licences, and new exports. The marketable gas forecasts developed for scenarios A and B are shown in Figure 4. Alberta domestic consumption of natural gas is also shown.

3. SULPHUR DIOXIDE EMISSIONS

Sulphur dioxide emissions are associated with natural gas production, oil sands, electric power generation, and other industrial operations, including conventional crude oil production, refineries, fertilizer plants, pulp and paper mills, and other manufacturing industries. Residential and commercial heating and transportation are negligible sources of sulphur dioxide and are not assessed in this forecast.

3.1 NATURAL GAS PROCESSING

A major portion of Alberta's marketable natural gas is obtained from sour raw gas. When the gas is produced, it is sweetened to remove the hydrogen sulphide and, where economically and technically feasible, the hydrogen sulphide is further processed to produce elemental sulphur. Sulphur recovery occurs at over 45 plants in Alberta and, in 1980, the average recovery of sulphur was in excess of 97.5%.

To develop a forecast of emissions from the natural gas industry, the ratio of sulphur produced to marketable gas delivered is analyzed, and a forecast for the sulphur production ratio is developed. The ratio is projected to decline from its present level of about $92\ \mathrm{t}.10^{6}\ \mathrm{m}^{-3}$ by 2000. Using this sulphur production ratio and the marketable gas forecast, the sulphur production forecast is developed.

The second stage of the forecast is to examine sulphur recovery efficiencies. Due to the large number of plants and the variety of processing systems, an industry average approach is taken in estimating the sulphur recovery trends and capabilities of plants using present, best practicable, and best available technology. Present technology is represented by existing Alberta sour gas industry capabilities and plans for upgrading

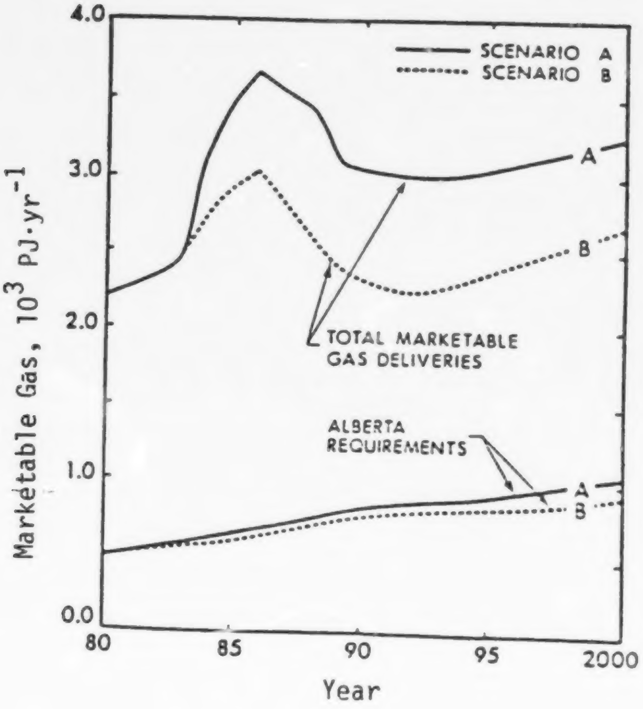

Figure 4. Marketable natural gas.

and bringing on new plants, and it is projected that by 2000 the present technology recovery level will be about 98.5%. A linear improvement from the present situation is anticipated. If best practicable technology is adopted by all existing and new plants, a level of recovery equal to 99% is anticipated by 2000 and, if best available technology was applied to all operations, including flaring operations, levels of at least 99.5% could be achieved by 2000. It is not expected that best available technology could be implemented until 1990 and, until that time, recovery levels would be the same as those for best practicable technology.

Figure 5 shows the forecast emission levels for the two growth scenarios and for the three levels of sulphur recovery technology.

3.2 OIL SANDS

Sulphur dioxide emission control from oil sands operations considers the two existing commercial plants and the potential for both in-situ and mining type. For new plants, it is assumed that they would meet the 3.15 t of sulphur dioxide emission per 1000 m^3 of bitumen to upgrading and that this would represent best practicable and best available technology.

For the two existing plants, present technology is expected to yield emissions less than or equal to about 90% of maximum licenced emissions. The applications of best practicable technology is expected to reduce emissions to 70 and 40% of current maximum licenced levels by 1987 and 1992, respectively. If best available technology is applied, it could be implemented by 1990 and result in emission reduction to 20% of current maximum licence levels.

Figure 6 shows the forecast sulphur dioxide emissions for the oil sands industry.

3.3 ELECTRICAL POWER GENERATION

Alberta derives approximately 90% of its electrical energy from coal-fired power plants and this is expected to be the situation throughout the forecast period. Coal burned in existing plants contains an average of about 0.26% sulphur and, as we progress through the forecast period, this

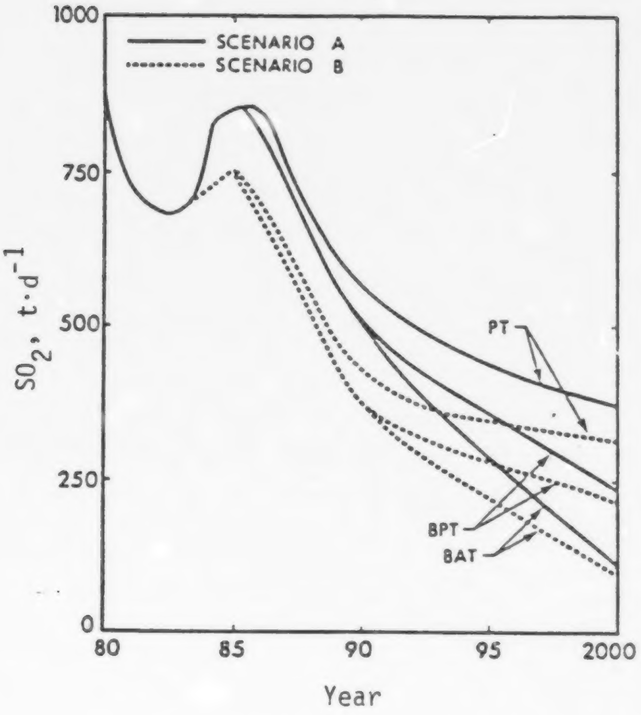

Figure 5. Natural gas industry.

average percentage is expected to increase due to the need to use coals that are somewhat richer in sulphur.

The forecast for emissions using present technology assumes no post-combustion emission control or pre-combustion coal cleaning to reduce sulphur dioxide emission levels. For best practicable technology, no control is applied to existing and presently approved plants, and, for all future plants (after about 1988 to 1900), emission levels are assumed to meet the federal emission guideline of 259 $ng \cdot J^{-1}$ of heat input for coal-fired power plants.

With the adoption of best available technology, phased in within 5 years after 1990 for all existing and future plants, emissions equivalent to about 40 $ng \cdot J^{-1}$ of heat input are projected for the last portion of the forecast period.

These emissions forecasts are summarized in Figure 7.

3.4 OTHER INDUSTRIES

All other industrial sectors are examined individually and these emissions are collectively summarized under the category of Other Industries. Sulphur dioxide emissions from this group, which includes conventional crude oil, fertilizer, pulp and paper, refineries, and other manufacturing operations, are less than 200 $t \cdot d^{-1}$ and represent less than 12% of total emissions.

With present and best practicable control technology for these industries, sulphur dioxide emissions are expected to be about the same and are outlined in Figure 8. With the application of best available technology, emission levels are projected to be reduced by about 50% by 2000.

4. OXIDES OF NITROGEN

Oxides of nitrogen emissions are estimated for all sectors of the Alberta economy based on fuel (coal, oil, gas, and other liquid fuels) consumption. Forecasts of fuel consumption are based on the same population, marketable gas deliveries, electrical energy, oil sands, and other industrial development forecasts that were previously discussed and used to develop the sulphur dioxide emission forecasts.

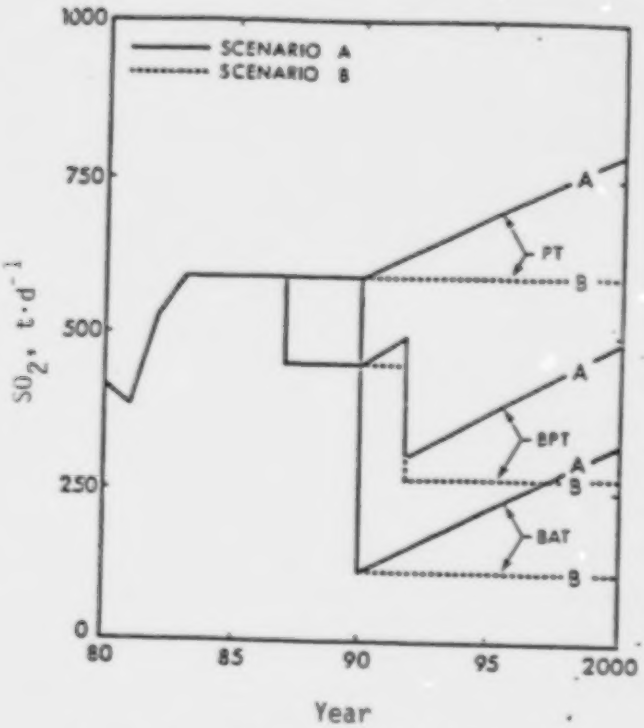

Figure 6. Oil sands industry.

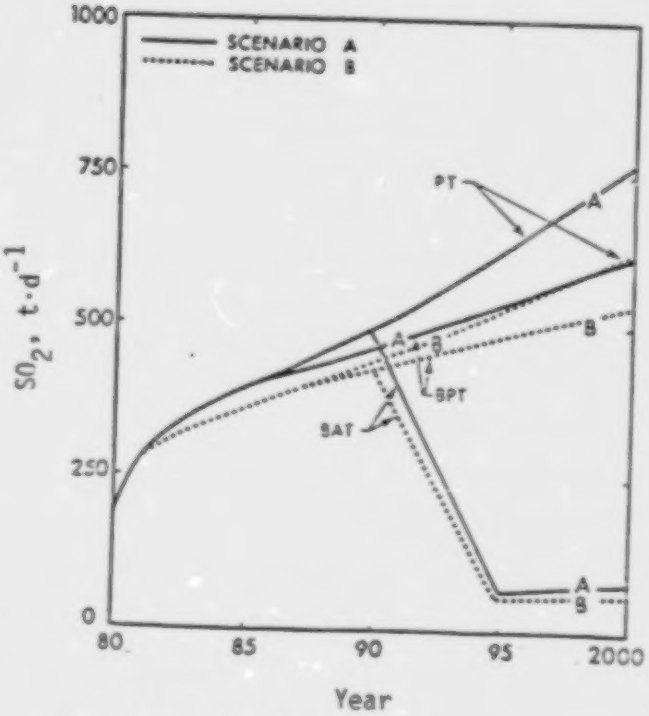

Figure 7. Electric power.

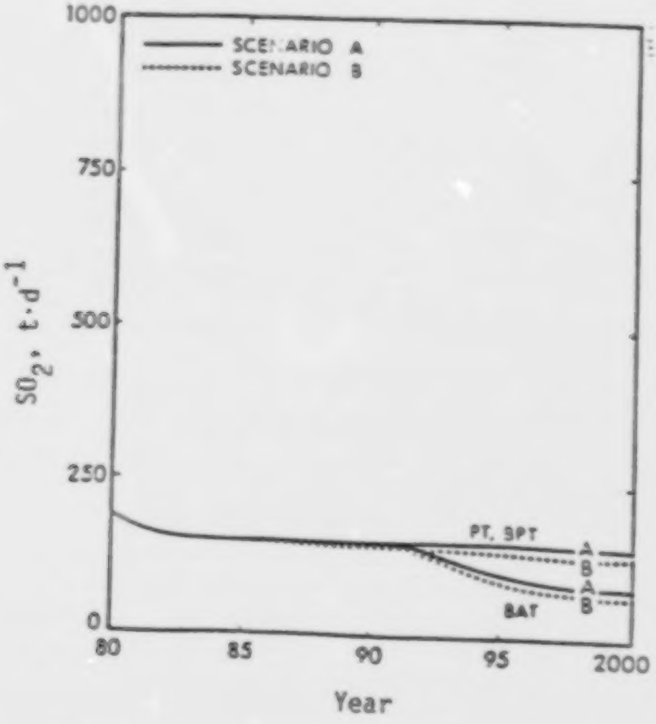

Figure 8. Other industries.

Oxides of nitrogen are emitted by essentially all industrial operations and, in addition, by residential and commercial heating facilities and by the transportation sector. The transportation sector, which includes passenger cars, commercial vehicles, and railway locomotives, represents about 40% of total oxides of nitrogen emissions throughout the forecast period.

4.1 NATURAL GAS INDUSTRY

Sources of emission in the natural gas industry are associated with field, gathering, processing, injection, transportation and distribution, and reprocessing operations. The point sources are reciprocating engines, gas turbines, heaters, boilers, and incinerators.

Historical data for total fuel consumption by the gas industry and an assessment of fuel consumption by source category on a per unit of marketable gas basis is used to develop the emission forecast. In addition, a recent report (Zelensky 1982), examining oxides of nitrogen control technology for compressor engines used in the natural gas industry, is used in conjunction with a fuel gas consumption study report (Berlie et al. 1982) to forecast emissions, assuming present, best practicable, and best available control technology.

The resultant forecasts of oxides of nitrogen emissions are shown in Figure 9.

4.2 ELECTRIC POWER GENERATION

Emissions from gas-fired and coal-fired electric utility boilers are predicted. Oxides of nitrogen emissions from gas-fired boilers are essentially all 'thermal NO_x', while the emissions from coal-fired boilers are mostly 'fuel NO_x'. For existing gas-fired boilers, emission levels are about 113 ng $NO_x \cdot J^{-1}$ of heat input compared to the new federal guideline of 86 ng $NO_x \cdot J^{-1}$ and for existing coal-fired boilers, levels are about 184 ng $NO_x \cdot J^{-1}$ of heat input compared to the guideline levels of 258 ng $NO_x \cdot J^{-1}$.

Existing average emission levels for Alberta are taken as representative of present technology. For best practicable and best

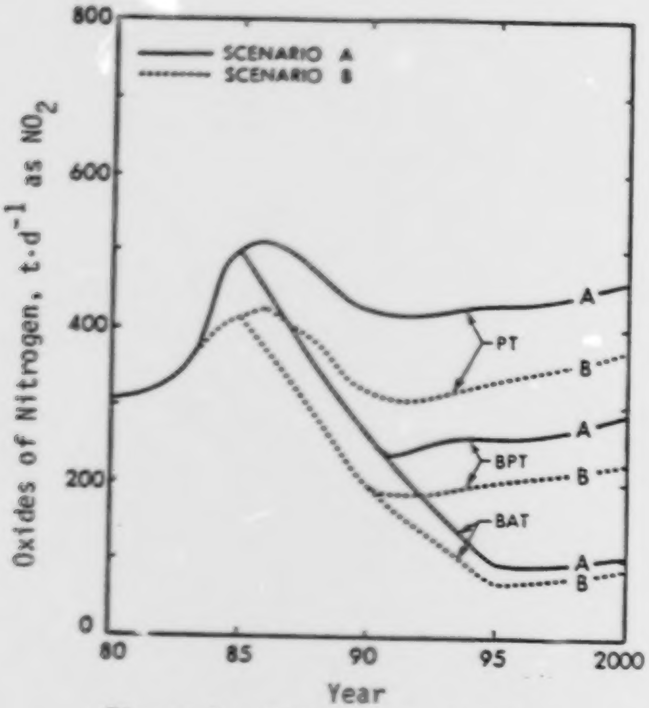

Figure 9. Natural gas industry.

available technology, reductions to these levels are estimated based on literature, including manufacturers' information, regarding NO_x reduction technology.

The forecast emissions from the electric utility sector are shown in Figure 10.

4.3 OIL SANDS

Oxides of nitrogen emissions from this sector are based on estimated coke, natural gas, and internal gas consumption for fuel purposes. Emission factors for each fuel type and for present and upgraded combustion and emission control technology are developed and applied to the fuel consumption forecasts to yield emission forecasts.

The results are shown in Figure 11.

4.4 OTHER INDUSTRIES

Emissions for all other industries are based on natural gas fuel consumption estimates and the application of improved combustion technology and emission control equipment. As with sulphur dioxide, this category is a minor contributor relative to total oxides of nitrogen emissions for Alberta.

Projected emissions are shown in Figure 12.

4.5 RESIDENTIAL AND COMMERCIAL

Oxides of nitrogen emissions from these two sources are based on gas, propane, and fuel oil consumption forecasts and, in total, they are small relative to total emissions in Alberta. New burners characteristic of best practicable technology may result in reduced emissions starting in 1985, and new heating systems and burners representative of best available technology may result in further reductions after 1990.

The emission forecasts are shown in Figure 13.

4.6 TRANSPORTATION

Environment Canada's Urban Road Transportation Emission Inventory model is used to predict passenger car and commercial vehicle emissions of

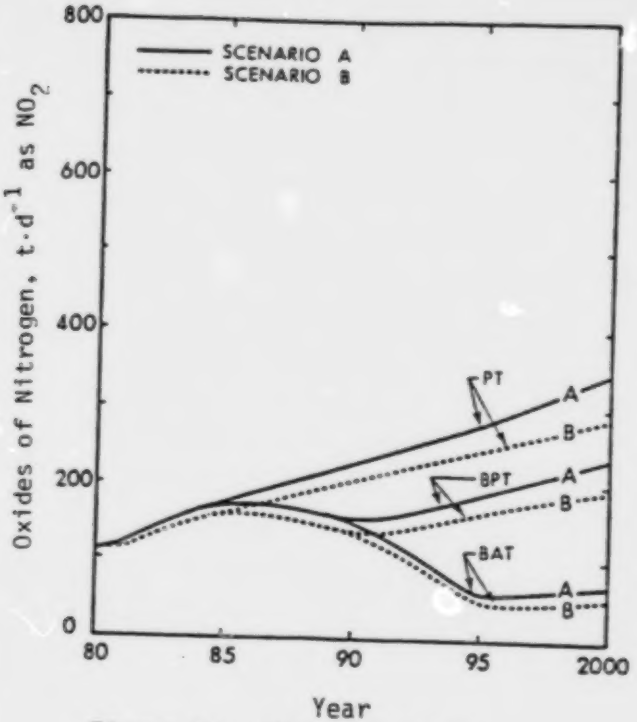

Figure 10. Electric power.

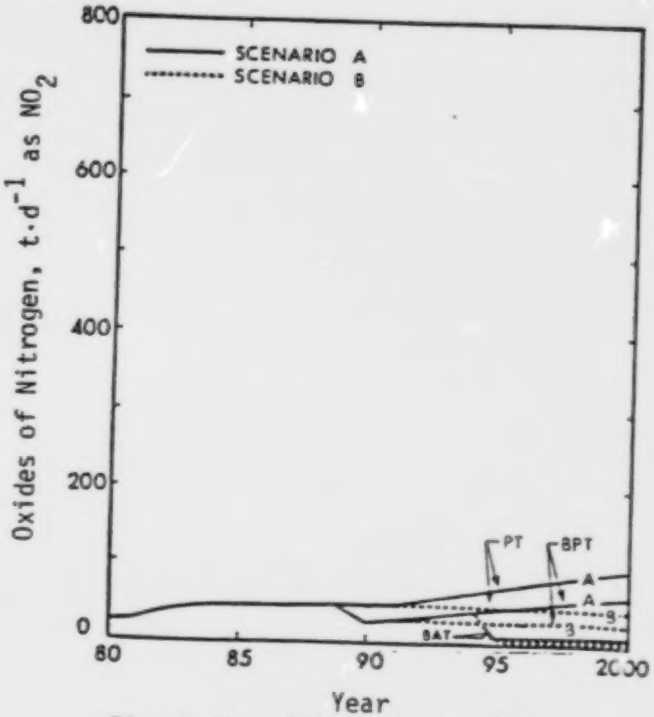

Figure 11. Oil sands industry.

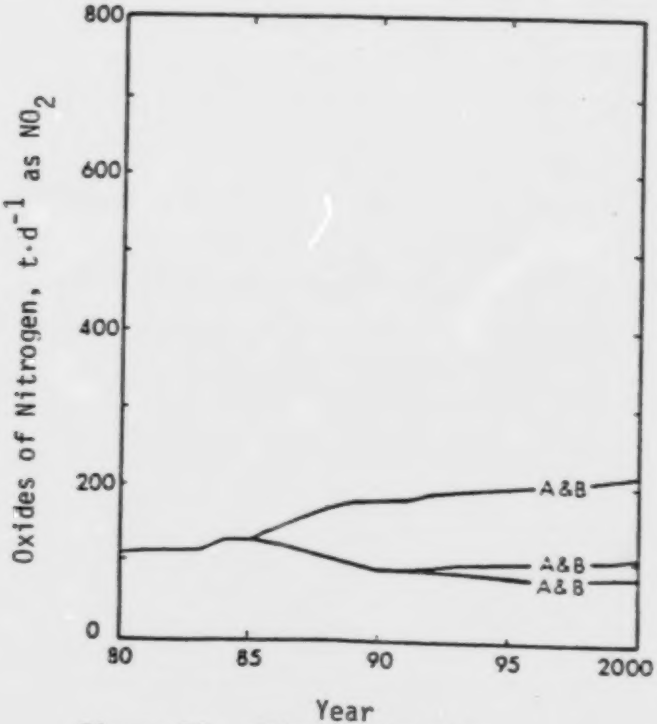

Figure 12. Other industries.

oxides of nitrogen for the vehicle growth forecast developed for Alberta. This model considers in-use vehicle performance and age distribution as well as emission control policies that represent present, best practicable, and best available technology.

In addition, emission factors based on fuel consumption are used for rail locomotive industry to estimate oxides of nitrogen emissions from this transportation mode. Of the transportation sector, railways are a small source (15% or less) of oxides of nitrogen.

The emission forecast for the transportation sector is shown in Figure 14.

5. SUMMARY

Emissions of both sulphur dioxide and oxides of nitrogen are forecast to increase significantly by the year 2000 if present technology is applied. However, if best practicable technology is used, emission levels in 2000 are forecast to be the same as, or slightly less than, present emissions. In addition, if best available technology is implemented, substantial reductions in emission levels can be achieved even though the individual sources are expected to grow in number due to the continued economic growth of Alberta.

The emissions for the two growth scenarios and for the three levels of technology are summarized graphically for sulphur dioxide in Figure 15 and oxides of nitrogen in Figure 16. These graphs demonstrate which sectors are the most significant contributors of emissions, and where research and development efforts should be directed to minimize emission increases.

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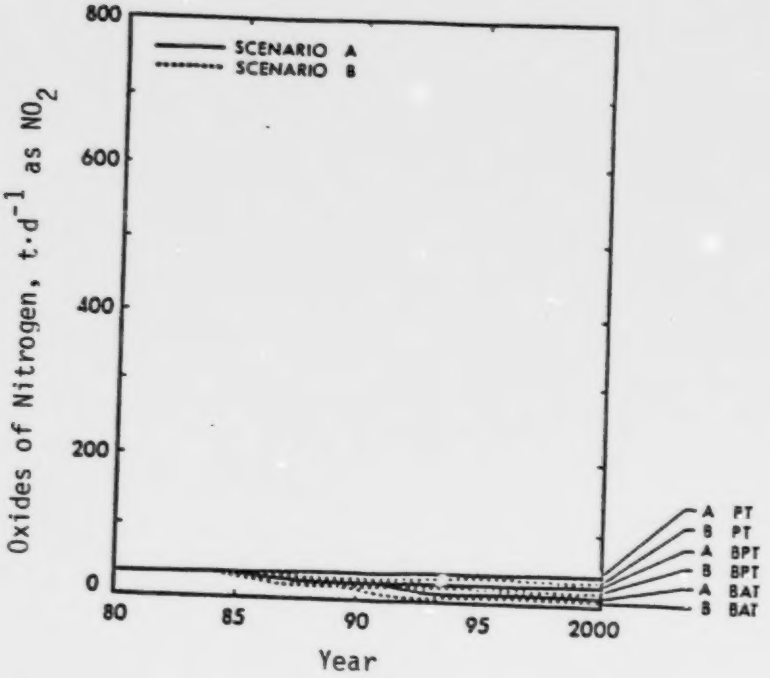

Figure 13. Residential and commercial.

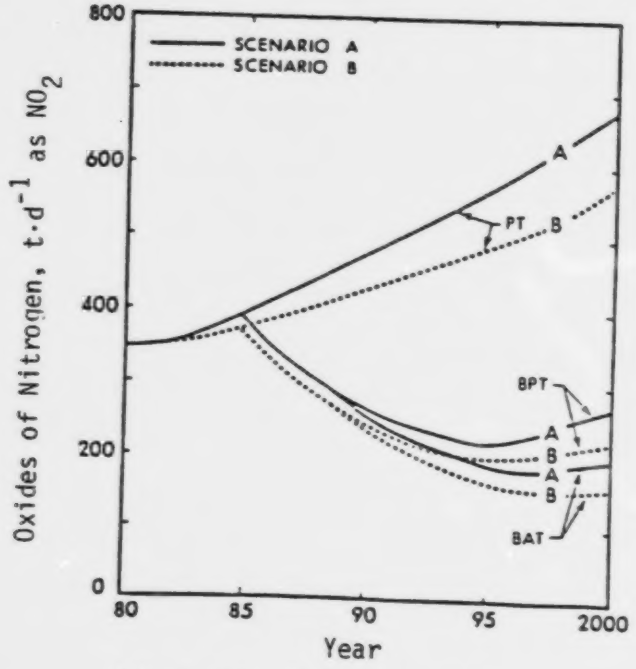

Figure 14. Transportation.

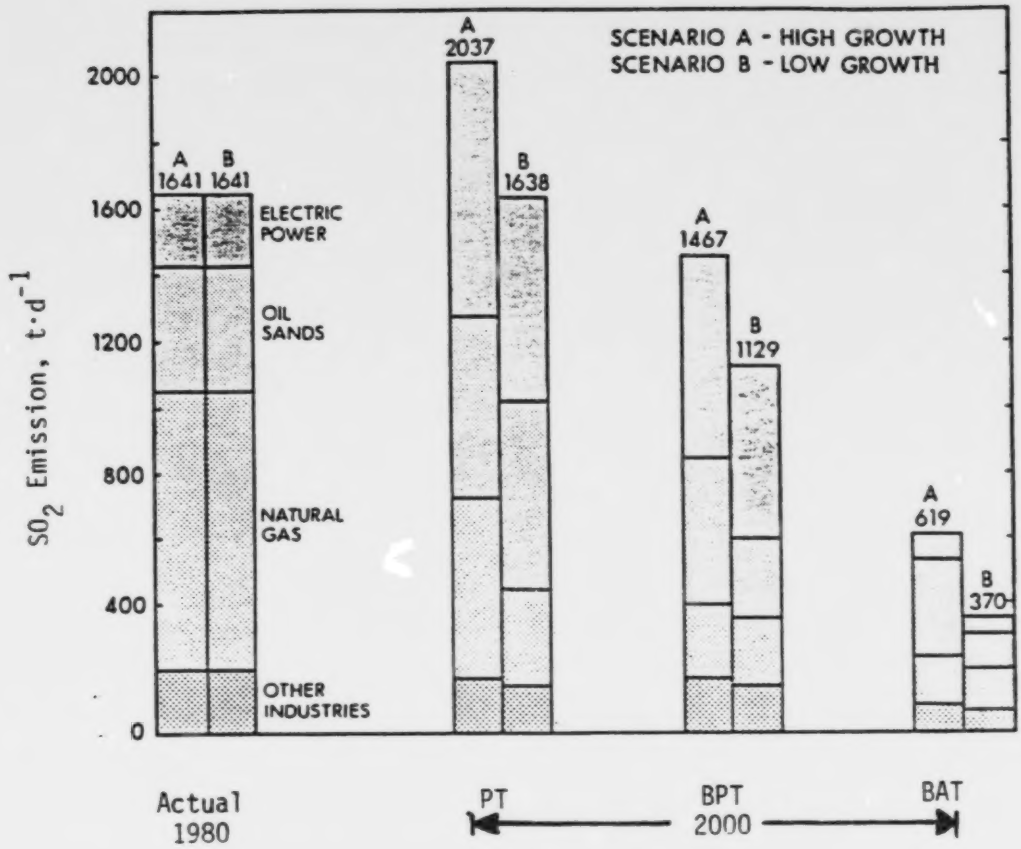

Figure 15. Emission comparison by sector and technology.

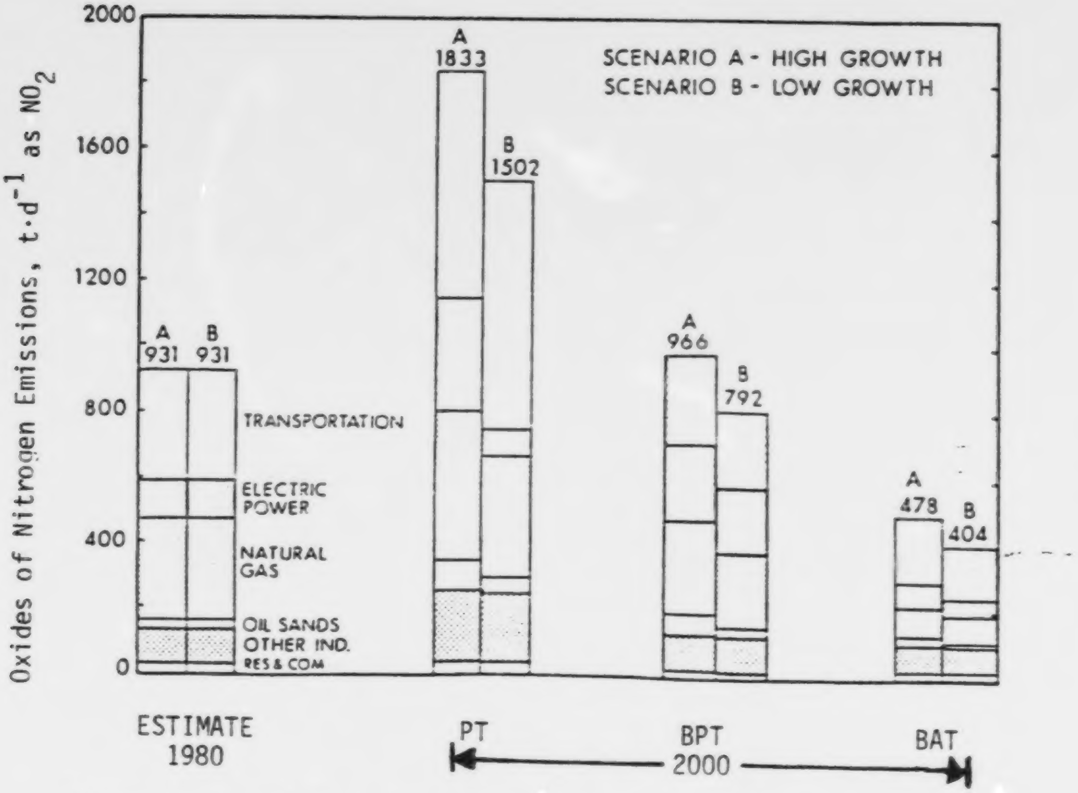

Figure 16. Emission comparison by sector and technology.

Colley, D.G., R.W. Poon, M.J. Zelensky, and L. Zanzotto. 1984. Alberta oxides of nitrogen emission forecast 1980 - 2000. Prep. for Alberta Environment, Research Management Division by Western Research, Division of Bow Valley Resource Services Ltd. RMD Report 83/26. 101 pp.

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ATMOSPHERIC MEASUREMENTS, MONITORING, AND MODELLING OF ACID-FORMING EMISSIONS IN ALBERTA

by

E. Peake[1], R.P. Angle[2], and H.S. Sandhu[3]

ABSTRACT

The status of the measurement, monitoring, and modelling of acid-forming emissions in Alberta is reviewed in the context of managing an integrated environmental system. The need for sensitive sampling methods for use in studies such as the Acid Deposition Research Program is apparent and one such system, the Kananaskis Atmospheric Pollutant Sampler is described and preliminary results presented. Future thrusts in the areas of measurement, monitoring, modelling, and management of importance to Alberta are outlined.

[1] Kananaskis Centre for Environmental Research, The University of Calgary, Calgary, AB

[2] Pollution Control Division, Alberta Environment, Edmonton, AB

[3] Research Management Division, Alberta Environment, Edmonton, AB

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The emissions of sulphur dioxide and nitrogen oxide from all sources in Alberta during 1982 amounted to about 488 000 and 353 000 t, respectively. These primary emissions may be deposited in the ecosystem directly or be converted to secondary air pollutants prior to deposition. In order to understand the physical, biological, and health effects of these pollutants, it is necessary to measure, monitor, and model atmospheric diffusion, transport, transformation, and deposition processes.

The words 'measure, monitor, and model' are intimately connected and have specific meanings in atmospheric sciences. Measurements are determinations of the amount of an atmospheric pollutant present, and are made over a limited period of time using simple or sophisticated methods. Monitoring consists of continuous or periodic measurements over a long period of time to meet long-term objectives; for example, to define trends, to check on compliance with standards/guidelines, or to study relationships among variables. Modelling refers to numerical techniques or methodologies, based upon physical principles, for estimating pollutant concentrations and depositions in space and time as a function of the emission distribution and the attendant meteorological and geophysical conditions.

A complete literature review on atmospheric measurements, monitoring, and modelling is beyond the scope of this paper. Recent reviews have covered measurement and monitoring activities in North America, including general processes (Fowler 1984), dry deposition (Sehmel 1980), and worldwide modelling activities (Weber 1982; Fronza and Melli 1982; Canada-United States Memorandum of Intent Final Reports 1982). This paper outlines the interacting components of an environmental system, examines Alberta studies, describes current activities, and identifies additional informational needs.

2. AN INTEGRATED ENVIRONMENTAL SYSTEM

Any phenomenon that involves the interaction between two or more components can be called a system. An integrated environmental system linking air pollutant emissions to environmental effects is depicted in Figure 1. Each of the three subsystems is subject to the four activities

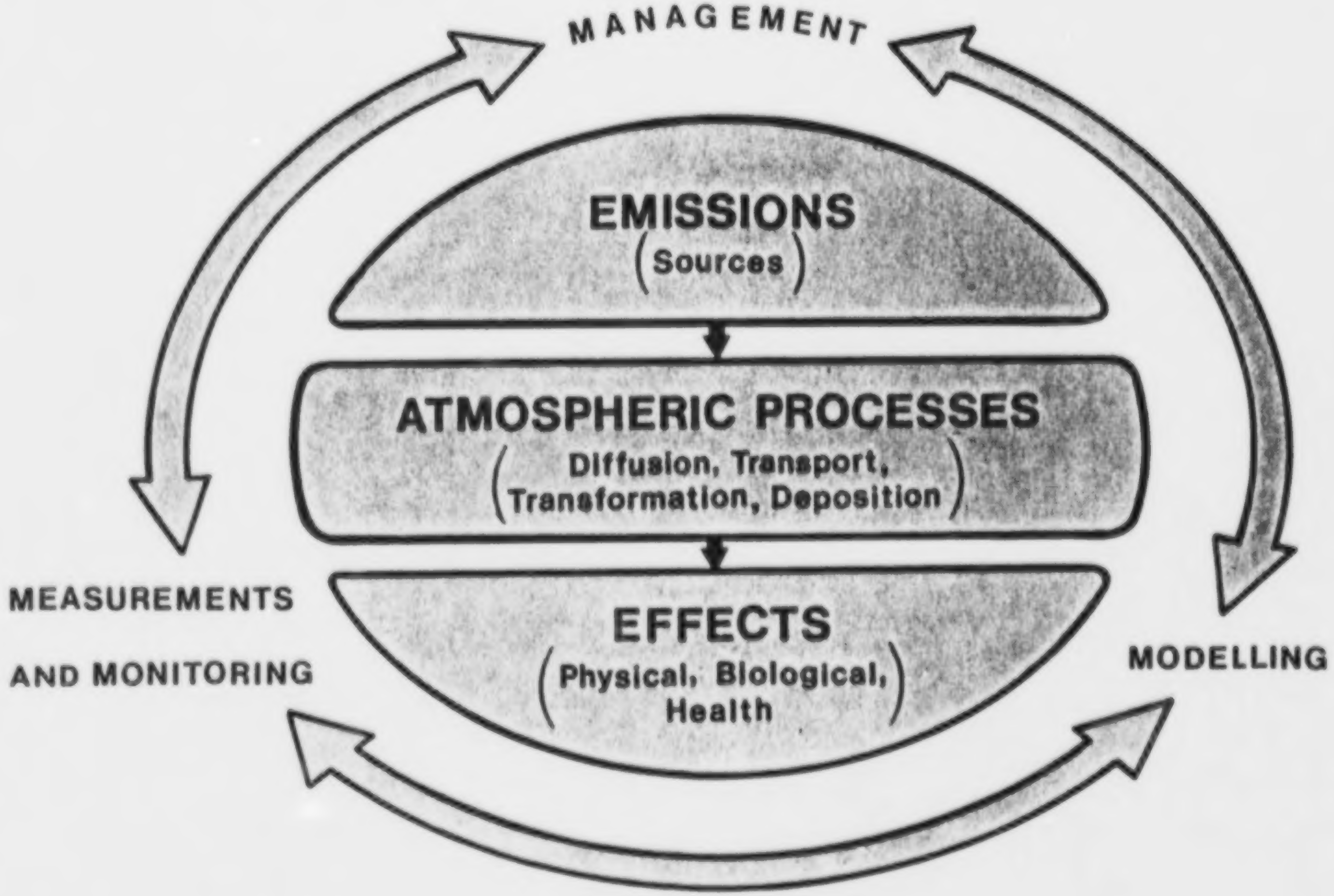

MANAGEMENT
EMISSIONS
(Sources)
ATMOSPHERIC PROCESSES
(Diffusion, Transport, Transformation, Deposition)
EFFECTS
(Physical, Biological, Health)
MEASUREMENTS AND MONITORING
MODELLING

Figure 1. An integrated environmental system.

of measurement, monitoring, modelling, and management in the broadest sense of the words. For instance, measurements are used to test models, which are used to do interpolations and extrapolations, and in turn are used for making management decisions. The decisions may prompt further measurements and the cycle is repeated as often as necessary to achieve the desired end results. In some circumstances, not all of the activities are required. Measurements, monitoring data, and modelling forecasts are inputs to management and, in turn, are affected by management.

A representation, abstraction, or simplification of a system is called a model. A model serves to formalize knowledge by integrating observations and theories, and to test our understanding of the processes involved. A model can predict hypothetical future states of a system or reconstruct past states that were not observed. The model can go beyond known circumstances and allow the study of a system under conditions that we are not yet able to observe or create, or may never be able or desirous of observing or creating. It may yield information about the behaviour of the complete system that is not obvious from the knowledge of individual parts, and can generate hypotheses for further testing. The interplay of model and empiricism in alternating series is a most powerful scientific tool. Once forecasts are available, it then becomes possible to study alternative actions; i.e., access competing scenarios required to make management decisions. For example, resources can be allocated in various ways to optimize chosen conditions within the system.

3. MEASUREMENTS AND MONITORING

3.1 STANDARD METHODS

3.1.1. Gaseous Pollutants

Techniques for the measurement and monitoring of ambient concentrations of the most common gaseous atmospheric pollutants (SO_2, H_2S, NO, NO_2, O_3, and CO) are well established and are used extensively by industrial and government monitoring networks in Alberta, as well as for research programs within the province. A review of these activities is beyond this paper, but some examples are:

1. The network of nine comprehensive and continuous air monitoring stations used by Alberta Environment to monitor urban air quality.
2. The Strathcona Industrial Compliance Network developed by an association of 10 industrial plants to monitor air quality in the eastern portion of the City of Edmonton and the adjacent area of the County of Strathcona (Docken et al. 1985).
3. A number of networks operated by private companies to monitor air quality in the vicinity of major industrial operations. These networks generally monitor H_2S, SO_2, wind speed, and wind direction, and consist of up to five air quality monitoring trailers.
4. The extensive baseline information on air, precipitation, and other environmental parameters obtained in northeastern Alberta by the Alberta Oil Sands Environmental Research Program (AOSERP), Suncor, and Syncrude.
5. The West Whitecourt Case Study, an interdisciplinary research program to determine the consequences of chronic exposure of the forest ecosystem to low concentrations of sulphur gas emissions (Legge et al. 1981).
6. The heavily instrumented monitoring sites of the Acid Deposition Research Program which continuously monitor seven gaseous pollutants and intermittently monitor four others. Eleven meteorological parameters are also monitored and particles and precipitation are collected for subsequent chemical analysis. Two sites are located near Crossfield, Alberta and the third, a background air quality monitoring station, is situated at the Fortress Mountain ski area in the Kananaskis Valley. These stations are to provide air quality information for use in assessing the possible impacts of industrial emissions on air, water, land, and human systems.

3.1.2 Aerosols

Atmospheric aerosols fall into two main categories: (1) large particles of greater than 1.0 μm diameter, derived from the earth's crust and reflecting its composition; and (2) particles emitted with, or generated from, gaseous emissions and generally in the size range of 0.1 to 1.0 μm, the accumulator mode. These particles consist largely of ammonium nitrate and ammonium sulphate, but include sulphuric acid which exists as an aerosol.

The monitoring of atmospheric aerosol concentrations is usually carried out on an integrated basis, often with 24 h of sample collection rather than on a real-time, continuous basis. Particles are collected on a filter medium and weighed, and may also be analyzed for chemical composition. Particles can be separated into two size fractions with the cutoff point being 2.5 μm. The smaller-sized fraction in this dichotomous sampling is of interest from the point of view of acidity as it may contain sulphuric acid. In Alberta, dichotomous samplers are operated in Calgary and Edmonton as part of the Canadian National Air Pollution Surveillance (NAPS) network. Samples are collected for 24 h every sixth day on the same schedule as high volume sampling. The weights of material collected and the nitrate and sulphate concentrations are determined.

3.2 NON-STANDARD METHODS

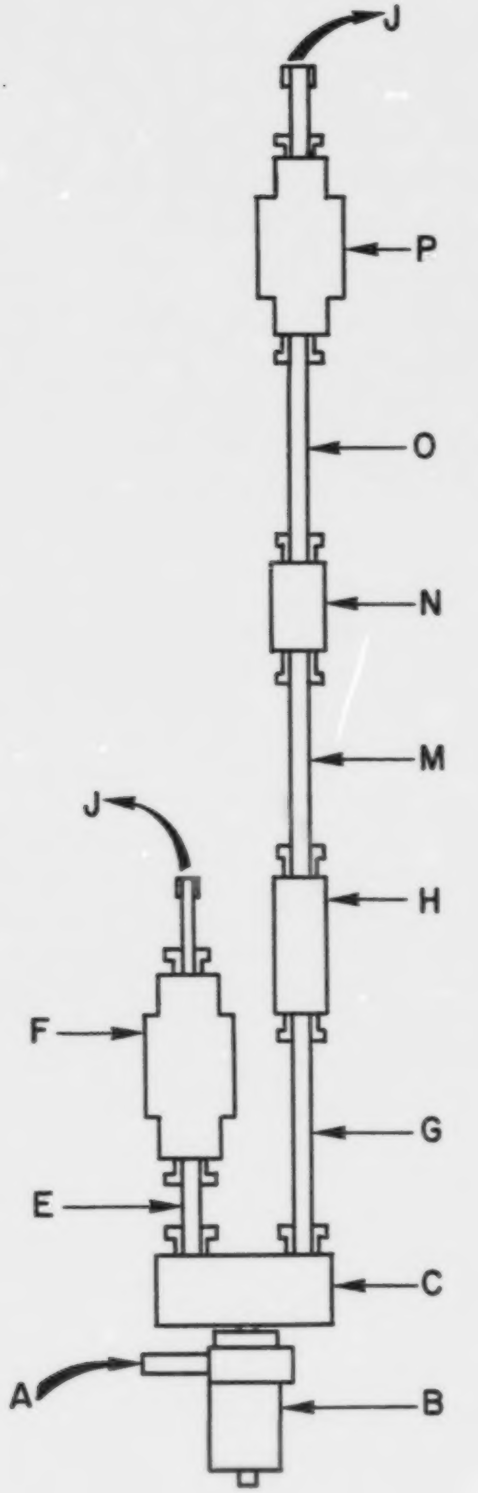
Although nitric acid is believed to be a major contributor to acidity, no standard method presently exists for the routine measurement of nitric acid in the atmosphere. The sampling system most frequently used is a dual filter pack consisting of a Teflon front filter to collect particles, followed by a nylon filter to collect gaseous nitric acid. The filters are then analyzed for nitrate by ion chromatography. In an inter-comparison of methods, Spicer et al. (1982) found that the dual filter system over-estimated nitric acid because particulate ammonium nitrate is volatilized from the Teflon filter and collected on the nylon filter. The method does, however, provide an excellent measure of total nitrate (Grosjean 1983).

This method was used to study nitric acid and particulate nitrate concentrations in the ambient atmospheres of Calgary and Edmonton and at a background site in the Kananaskis Valley, 70 km west of Calgary. Mean concentrations of inorganic nitrate in Calgary during the summer of 1980 were low, 0.51 $\mu g \cdot m^{-3}$, of which 0.26 $\mu g \cdot m^{-3}$ was volatile nitrate (nitric acid plus volatilized ammonium nitrate). During the period November 1982 to October 1983 in Edmonton, mean total nitrate was 1.16 $\mu g \cdot m^{-3}$, of which 0.30 $\mu g \cdot m^{-3}$ was volatile nitrate. The highest volatile nitrate concentrations were somewhat lower than those recorded in Toronto in 1979 (Barrie et al. 1979). Background mean volatile nitrate concentrations recorded in the Kananaskis Valley in August 1980 were 0.22 $\mu g \cdot m^{-3}$ with total nitrate being 0.35 $\mu g \cdot m^{-3}$(Peake et al. 1983, 1985).

3.3 KANANASKIS ATMOSPHERIC POLLUTANT SAMPLER (KAPS)

A sampling system developed and tested by the Kananaskis Centre for Environmental Research at the University of Calgary provides a method for collecting an integrated sample of gases and of aerosols that is free from any of the shortcomings of the earlier methods. Acid gases, ammonia, and particles were collected separately and there is no reaction of gases to change the composition of particles. Nitric acid is collected without interference from volatile ammonium nitrate.

This system was developed as part of a study of acid deposition in Alberta (ADRP, the Acid Deposition Research Program). The heart of the system is the annular denuder tube developed by Possanzini et al. (1983). In the Kananaskis Atmospheric Pollutant Sampler (KAPS) system, the annular denuders are utilized to capture acid gases, primarily nitric acid, nitrous acid, and sulphur dioxide, as well as ammonia, for subsequent analysis by ion chromatography or colorimetrically. The design of the KAPS system is shown in Figure 2. Three annular denuder tubes are connected in series. Each denuder tube consists of an outer glass tube having a three-quarter inch outside diameter and a 13.2 mm inside diameter, and an inner tube of 10.0 mm outside diameter. The annulus walls of the first denuder tube (G) are coated with sodium carbonate and retain nitric acid, nitrous acid, sulphur dioxide, and other acid gases. The tube also retains some nitrous oxide (about 5%) which interferes in the subsequent analysis of nitrous acid by ion chromatography. Some particles may also be deposited in the tube but their effect is likely to be negligible as laminar flow is maintained in the



A. Inlet

B. Cyclone

C. Manifold

E. 3/4" Teflon Tube

F. Dual Filter Holder

G. Na_2CO_3 Annular Denuder

H. Expansion Coupler

J. Quick Connect Fitting (to flow controller and pump)

M. Second Na_2CO_3 Annual Denuder

N. Coupler

O. Citric Acid Annular Denuder

P. Dual Filter Pack

Figure 2. The Kananaskis Atmospheric Pollutant Sampler (KAPS).

sampling system. The second denuder tube (M) retains some of the remaining nitrous oxide (a further 5%), and is used to correct the nitrous acid value as determined from analysis of nitrite in the first denuder tube. The third denuder tube (O) is coated with citric acid and is used to collect ammonia. The system has been tested extensively in both laboratory and field trials, including tests in California, and has proven effective for the collection of acid and base gases.

Of particular interest is the ability of the KAPS system to collect nitrous acid. Measurements carried out in Calgary during the period 1985 June 24 to June 28 showed nitrous acid to be generally more abundant than nitric acid, whereas, during the period July 02 to July 07, nitric acid was usually dominant. Nitrous acid concentrations ranged from 0.05 to 1.24 $\mu g \cdot m^{-3}$, and nitric acid concentrations from 0.04 to 1.05 $\mu g \cdot m^{-3}$. Nitrous acid to nitric acid ratios varied greatly, from 0.18 to 14, and there were strong diurnal variations. Measurements of nitrous acid in other urban atmospheres are scarce but concentrations of up to 2.4 $\mu g \cdot m^{-3}$ were found by Sjodin and Ferm (1985) in Gothenburg, Sweden.

In Calgary, SO_2 was more abundant than nitric and nitrous acids, with mean daily concentrations ranging from 0.52 to 3.17 $\mu g \cdot m^{-3}$. During the period June 26 to July 06, ammonia was collected in Calgary using a citric acid annular denuder tube. Ammonia concentrations ranged from 1.9 to 14.5 $\mu g \cdot m^{-3}$.

The KAPS system also collects fine particles for chemical analysis. Large particles such as windblown dust are removed by a Teflon cyclone, and fine particles are collected on a Teflon filter. The cutoff point between the coarse and fine particles varies as a function of the desired sampling rate but generally is maintained at 2.0 μm. The KAPS system offers an advantage over standard filter packs as the particles collected on the filter medium are not subject to reactions with acid gases or ammonia because these gases have been previously removed by the annular denuder tubes.

Three sophisticated air monitoring trailers equipped with KAPS samplers are operated as part of the *ADRP*. Two are located near Crossfield, Alberta and the third, a background air quality monitoring station, is located at the Fortress Mountain ski area in the Kananaskis Valley. Preliminary data are shown in **Table 1**.

3.4 WET AND DRY SULPHUR DEPOSITION IN ALBERTA

Five stations in the Canadian Network for Sampling Precipitation (CANSAP) are located in Alberta. In addition, six precipitation monitoring sites have been operating since 1978 by Alberta Environment. These networks monitor the chemical composition of rainfall primarily for the major anions SO_4^{2-}, NO_2^-, and Cl^-, and the major cations NH^{4+}, Ca^{2+}, Mg^{2+}, and K^+, which represent the principal ions (excluding hydrogen) in precipitation. Hydrogen ion concentration is measured as pH.

Precipitation samples have been collected from the relevant Alberta stations on a monthly basis since 1978 and average data are shown in **Table 2**. These data were examined for chemical composition, spatial distribution, seasonal variation, temporal trend, acidity, and wet sulphate deposition (Lau and Das 1985). Alberta precipitation has an average pH of 5.5; calcium, sulphate, and ammonium ions are the predominant species, and the higher ion concentrations occur in southern Alberta. The relatively high concentration of calcium indicates a contribution from windblown dust. The large amounts of precipitation in the summer result in a lower ion concentration in the rainfall. No temporal trend was apparent. The average wet sulphate deposition in Alberta from 1978 to 1984, based on this data, was 8.9 kg $ha^{-1} \cdot yr^{-1}$ (kilogram per hectare per year).

The acid input to a receptor is derived from a combination of both wet and dry deposition. In the past, attention focussed on wet deposition but the importance of dry deposition is now widely recognized. Dry deposition of gases and particles is estimated to be 10 times greater than wet deposition in semi-arid areas of California (Liljestrand 1979).

Measurements of the relative amounts of wet and dry deposition in Alberta indicate that under our dry climatic conditions, dry deposition predominates by a factor of 5 (Caiazza et al. 1978; Legge et al. 1981). Walker et al. (1981) calculated that 7 to 9 $kg \cdot ha^{-1}$ of total sulphate S was deposited annually in a 4600 km^2 area, within which 10 major sources were

Table 1. Concentrations of pollutants, collected with the KAPS system, at three Alberta locations (preliminary data, no blank correction) ($\mu g \cdot m^{-3}$).

	PRIMARY GASES			SECONDARY GASES		PARTICULATES	
	NH_3	SO_2	NO_2[a]	HNO_2	HNO_3	NO_3^-	SO_4^{2-}
Background							
Mean	0.47	1.09	0.50	0.002	0.07	0.35	0.21
Std. Dev.	0.48	1.35	0.23	-	0.20	0.23	0.16
Minimum	0.01	0.11	0.21	0.000	0.01	0.05	0.01
Maximum	2.19	6.63	1.35	0.016	0.56	1.10	0.69
N	58	60	60	-	60	60	58
Site No. 1							
Mean	1.09	5.61	1.89	0.016	0.27	0.64	0.83
Std. Dev.	1.55	4.91	1.76	-	0.38	0.70	1.84
Minimum	0.00	0.34	0.15	0.000	0.00	0.07	0.05
Maximum	10.54	29.41	11.42	0.096	1.26	3.80	12.32
N	65	65	64	66	-	64	64
Site No. 2							
Mean	0.74	9.97	2.54	0.007	0.34	0.73	0.70
Std. Dev.	0.82	13.41	3.32	-	0.60	1.27	1.01
Minimum	0.03	0.27	0.41	0.000	0.05	0.00	0.04
Maximum	3.97	7.19	19.96	0.940	1.22	8.50	5.17
N	62	60	62	-	60	60	62

[a] by NO_x analyzer

Table 2. Volume-weighted averages of parameters measured for 1978 to 1984[a] ($\mu eq \cdot L^{-1}$).

	pH	SO_4^{2-}	NO_3^-	NH_4^+	Ca^{2+}	Mg^{2+}
Beaverlodge	5.17	28.9	10.0	25.8	35.3	8.8
Calgary	5.77	65.4	20.6	40.8	93.0	23.3
Coronation	5.46	39.3	16.6	15.7	32.3	8.7
Edmonton	5.45	39.0	16.1	29.6	26.1	10.9
Edson	5.61	31.6	8.6	8.2	33.5	7.1
Fort McMurray	5.26	38.4	11.6	3.4	59.5	31.3
Lethbridge	6.06	47.8	24.6	26.1	132.6	28.6
Red Deer	5.39	37.0	15.6	36.2	30.9	7.3
Rocky Mountain House	5.53	39.1	11.8	20.6	41.9	11.4
Suffield	5.60	50.9	19.9	70.6	48.4	18.5
Whitecourt	5.71	41.9	12.8	11.5	93.0	19.5
OVERALL	5.48	41.1	14.7	25.2	55.3	14.8

[a] Alberta Environment stations 1978 to 1984 except for Calgary (1979 to 1984); CANSAP stations 1978 to 1983.

licensed to produce 330 tonnes S per day. At distances greater than 40 km from the sources, the deposition rate varied from 4 to 6 $kg\cdot ha^{-1}$.

One approach to determining dry deposition is to measure the ambient concentration of the species of interest and to multiply this by an appropriate deposition velocity. Deposition velocity depends on the wind speed, stability, topography, the type of ground cover, and surface wetness. Many of these dependencies are not easily quantified. Measurements of mass balance, eddy flux, eddy accumulation, or profile techniques give deposition velocities that range over four orders of magnitude for gases and over three orders of magnitude for particles (Sehmel 1980).

A study of the deposition velocity of SO_2 to a field of barley was carried out in 1983 near Crossfield, Alberta using the atmospheric flux method (Chadder et al. 1984). Results indicated SO_2 deposition velocities of approximately 0.1 $cm\cdot s^{-1}$ in the evening and 1.0 $cm\cdot s^{-1}$ during morning daylight hours. This is close to the same range as reported by Fowler (1984) for wheat, a maximum of 1.2 $cm\cdot s^{-1}$ during the day and a minimum of 0.2 $cm\cdot s^{2}$ at night. During the study, SO_2 concentrations ranged from 0.2 to 116 $\mu g\cdot m^{-3}$ but generally were in the 5 to 30 $\mu g\cdot m^{-3}$ range. Typical averaged values of deposition velocities as summarized by Denison et al. (1979) are: 0.3 $cm\cdot s^{-1}$ for snow, 0.6 $cm\cdot s^{-1}$ for soil, 1.1 $cm\cdot s^{-1}$ for grass, 1.1 $cm\cdot s^{-1}$ for water, and 1.6 $cm\cdot s^{-1}$ for forest. In a study of acid deposition in the western United States, Hidy and Young (1986) used mean deposition velocities of 0.5 $cm\cdot s^{-1}$ for SO_2, 0.2 $cm\cdot s^{-1}$ for $SO_4{}^{2-}$, 0.1 $cm\cdot s^{-1}$ for NO_2, 1.0 $cm\cdot s^{-1}$ for $HNO_3{}^{-1}$, and 0.2 $cm\cdot s^{-1}$ for $NO_3{}^{-1}$. Using these velocities, the estimated dry deposition of sulphate (SO_2 and particulate sulphate) in rural and background areas of the western United States is 7 $kg\cdot ha^{-1}\cdot yr^{-1}$, and of nitrate ($NO_2$, nitric acid, and particulate nitrate) is 5 $kg\cdot ha^{-1}\cdot yr^{-1}$.

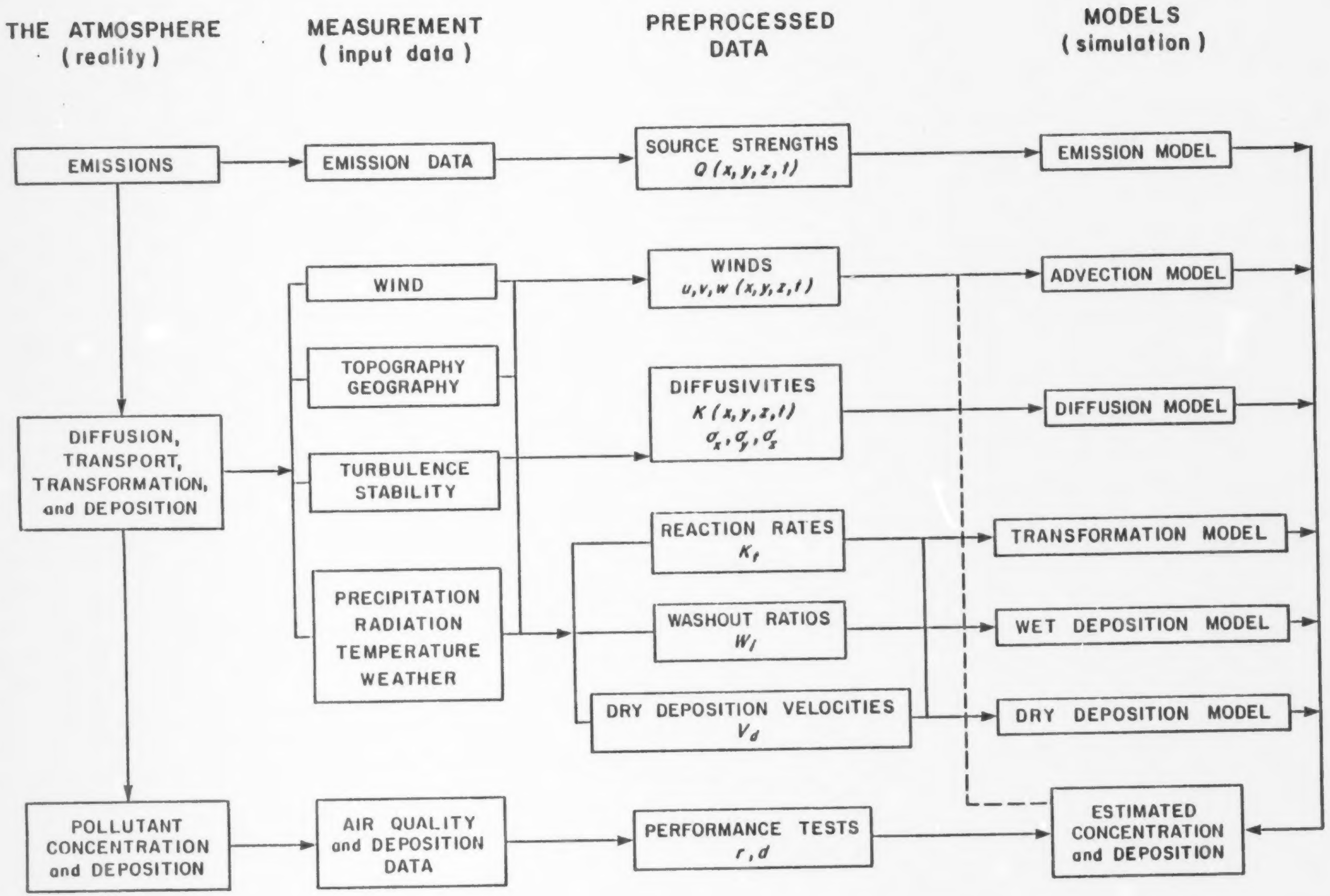
The inability to monitor dry deposition or accurately determine deposition velocities leads to large uncertainties in the estimates of total deposition. This makes it difficult to assess the present situation and to conduct the effects research needed to establish target loadings. Because management decisions are founded on comparisons between actual and desirable states, these uncertainties must be reduced and appropriate standards established.

4. ATMOSPHERIC POLLUTION MODELLING

4.1 NATURE AND USES OF MODELS

An atmospheric pollution model comprises a number of modules or submodels that represent the major processes governing the behaviour of airborne pollutants (**Figure 3**). The model is 'mathematics' because it consists of equations that relate various dependent and independent variables within the process and between processes. Thus, a volume of pollutant is released (emission), carried by the wind (transport), spread out by turbulence (diffusion), reacted chemically with other species and sunlight (transformation), and removed from the air by vegetation and soil through precipitation, gravitational settling, impaction, electrical attraction, Brownian motion, chemical reaction, and other surface collection mechanisms (deposition). In order to operate, a model must have a number of specific inputs obtained by processing the available measurements. The failure of outputs to compare favourably with actual measured concentrations or deposition can be caused by any of the components--input data, pre-processing algorithms, physical/chemical process models--or by the interaction between components. The lack of appropriate input data is a major impairment to model performance.

A decision-maker routinely faces a host of questions to which reasonable answers must be given quickly. Atmospheric pollution models allow the exploration of hypothetical situations and their consequences for air quality/deposition. Quantitative answers to "what if" questions provide the foundation for decisions that govern many day-to-day activities. Such models are tools that decision-makers employ to obtain some of the information that enters into their deliberations (Angle 1979). Some typical applications are summarized in **Table 3**. If environmental effects models (vegetation, surface water, health) could be developed and linked to atmospheric models, the value of information available to decision-makers would be greatly enhanced.


THE ATMOSPHERE
(reality)
MEASUREMENT
(input data)
PREPROCESSED
DATA
MODELS
(simulation)
EMISSIONS
EMISSION DATA
SOURCE STRENGTHS
Q (x, y, z, t)
EMISSION MODEL
WIND
WINDS
u, v, w (x, y, z, t)
ADVECTION MODEL
TOPOGRAPHY
GEOGRAPHY
DIFFUSIVITIES
K (x, y, z, t)
σx, σy, σz
DIFFUSION MODEL
DIFFUSION,
TRANSPORT,
TRANSFORMATION,
and DEPOSITION
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STABILITY
REACTION RATES
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TRANSFORMATION MODEL
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RADIATION
TEMPERATURE
WEATHER
WASHOUT RATIOS
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DRY DEPOSITION VELOCITIES
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CONCENTRATION
and DEPOSITION
AIR QUALITY
and DEPOSITION
DATA
PERFORMANCE TESTS
r, d
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CONCENTRATION
and DEPOSITION

Figure 3. Flow scheme showing modules or elements in an atmospheric pollutant model.

Table 3. Air pollution model applications.

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1. AIR POLLUTION IMPACT ANALYSIS
   - Existing sources
   - Plans involving changes in existing emission patterns
   - Government policies affecting emission patterns directly or indirectly
   - Alternative site selection (minimization of adverse impacts)

2. ATTAINMENT OF AIR QUALITY/DEPOSITION STANDARDS
   - Monitoring network design
   - Formulation of control policies
   - Licencing and regulation
   - Meteorologically controlled emission systems
   - Stack design

3. CHARACTERIZATION OF EXISTING AIR QUALITY/DEPOSITION IN MULTI-SOURCE AREAS (Analysis of ambient concentrations/depositions of primary and secondary pollutants)
   - Determination of spatial and temporal patterns
   - Hot spot identification
   - Worst case identification
   - Determination of source contributions
   - Separation of anthropogenic and natural causes
   - Data base error diagnosis (emissions inventory and monitoring)

4. HISTORICAL AIR QUALITY/DEPOSITION TREND ANALYSIS
   - Delineation of changes caused by changes in weather, source distribution, and emissions
   - Selection standards

5. SUPPORT FOR EFFECTS AND ECONOMIC STUDIES (Distribution and magnitude of concentrations/depositions)

4.2 MODELLING IN ALBERTA

4.2.1 Short Range (0 to 100 km)

The early work of Benjamin (1975) showed that at the 'hot spot' (position of the maximum) downwind of a sour gas plant, the dry deposition flux could be between 10 and 100 times greater than the deposition flux occurring at a distance of 100 km. A value of about 2 $kg \cdot ha^{-1} \cdot mo^{-1}$ (sulphur) was calculated at a distance of 3 km for a typical sour gas plant in July. He also calculated that about 25% of the sulphur in the plume would be deposited within 100 km. Model sensitivities drew attention to the need for better information on the heights and strengths of elevated inversions and the frequency of ground-based inversions.

Walmsley and Bagg (1977) used a modified version of the EPA Climatological Dispersion Model to estimate dry deposition around the Suncor oil sands plant. Maxima of about 16 $kg \cdot ha^{-1} \cdot yr^{-1}$ (sulphur) occurred 2 to 3 km SSE and NNW of the plant. As with Benjamin, a deposition velocity (ratio of deposition flux to ambient concentrations) of 1 $cm \cdot s^{-1}$ was used.

A model developed by Western Research and Development (1978) allowed deposition velocity to be a function of atmospheric stability and incorporated wet deposition by the equilibrium scavenging theory. Wet deposition within 40 km of the source was found to be about one-tenth that of the dry, and the maximum total depositions were less than 6 $kg \cdot ha^{-1} \cdot yr^{-1}$ (sulphur).

Greater realism was added to this model by Alberta Environment (1984) incorporating, among other things, surface roughness, variable wind speed with height, and limited mixing. The annual deposition maxima for the small and medium sources were 5 to 10 km away from the source. The large source had a maximum 25 to 30 km away. The highest total deposition was found to be about 11 $kg \cdot ha^{-1} \cdot yr^{-1}$ of sulphur for the medium source. The annual total deposition resulting from a large continuous flare (emission 10 $t \cdot yr^{-1}$) was about half that associated with the medium gas plant. The total yearly sulphur deposition within a 100 km radius is about 24% of yearly sulphur emissions, except for the large gas plant, where the percentage is about 9%, due primarily to a very large plume rise and an associated penetration into the capping stable layer.

The frequency distribution model developed for the Alberta oil sands (Davison et al. 1981) uses more advanced boundary layer parameterizations to obtain concentration and deposition estimates. This model also has more powerful analyses capabilities than are available on traditional climatological models. The user can construct ground-level concentration statistics based upon user-selected criteria for inclusion/exclusion or weighting of time series realizations depending upon ambient meteorological conditions. In a recent comparison of model-predicted distributions and observed distributions (Nosal unpublished), the Kolmogorov Smirnoff test showed no significant differences with 99% confidence. Such a model should prove useful in relating air quality to vegetation effects. The development of an environmental response model to link the atmosphere and the biosphere is one of the goals of the Acid Deposition Research Program.

Until quite recently, short-range transport and deposition models contained either no chemical transformations at all or simply fixed percentages per hour. Bottenheim and Strausz (1981) developed a chemically reactive plume model describing the homogeneous gas-phase chemistry of a plume containing SO_2 and NO_x from an oil sands extraction plant. The oxidation rate for SO_2 in typical summer conditions was found to rise almost linearly to $2\%\cdot h^{-1}$ within 60 min of travel time, and then to increase more slowly. The rate was also found to be sensitive to the ratio of in-plume NO_x to ambient hydrocarbons. Emitted NO_x was 90% converted into PAN and nitrate within 4 h of travel time, whereas 10 to 18% of the SO_2 was converted to sulphate. These results compared favourably with available observations in the oil sands and elsewhere.

A detailed oxides of nitrogen conversion model was developed by Vet et al. (1982) to address the problem of NO_2 formation downwind of compressor stations. This model consisted of 38 reactions for the more generalized polluted atmosphere scheme of Bottenheim and Strausz (1978). Evaluation of this model against existing data is currently underway (Reid et al. 1985).

4.2.2 Medium Range (100 to 1000 km)

For the transport of material over larger distances, it is important to include the chemical transformations of SO_2 to sulphate and the emission of sulphates. The LRTAP model TRANS includes this conversion chemistry and was used by the Oil Sands Environmental Study Group to assess the possible long-term impact of oil sands development (Meteorological and Environmental Planning Limited 1982). The model also included nitrogen oxides emissions and subsequent nitrogen deposition. Weisman et al. (1982) reported that the long-term mean loading of sulphur had a peak value of 4.0 $kg \cdot ha^{-1} \cdot yr^{-1}$ in the region of Fort McMurray, with the wet component contributing 40%. The loading dropped to 1 $kg \cdot ha^{-1}$ within 300 km of Fort McMurray. Of the wet deposition, 90% was due to SO_2 and 10% to sulphates. Most of the SO_2 wet deposition occurred in winter, while most of the sulphate wet deposition occurred in the summer (Meteorological and Environmental Planning Limited 1982).

The long-term loading of nitrogen (wet plus dry) showed a peak rate of 0.24 $kg \cdot ha^{-1} \cdot yr^{-1}$ as nitrogen. The mean loading of sulphur in the range of 0 to 100 km was 3.7 $kg \cdot ha^{-1} \cdot yr^{-1}$, with wet deposition accounting for 40% of the deposition. In the distance range of 300 to 500 km, the average total loading was only 2.4 $kg \cdot ha^{-1} \cdot yr^{-1}$, with wet loading accounting for 50%. It was also found that approximately 25% of the sulphur emissions are deposited within 200 km of the sources, 50% are deposited within the first 500 km, and 75% within 1000 km. For nitrogen, the corresponding fractions are 21%, 42%, and 60% of annual emissions.

At LRTAP Workshop No. 4 (1985), "Requirements for Mesoscale Acid Deposition Modelling and Monitoring in Western Canada," a need for three types of models was identified: (1) urban photochemical, (2) mesoscale deposition, and (3) advanced complex deposition and oxidant. Important processes that often go unrepresented in such models were also identified as convective and frontal storms, flow in complex terrain, rain and snow scavenging, influences of soil particles, and cloud physics and chemistry. The Western Mesoscale Modelling Task Group (1985), which followed the workshop recommendations, added a fourth category of model types, statistical models, to provide for annual or seasonal loading estimates at more reasonable cost. The Task Group reviewed more than 100 available models, made the selections shown in **Table 4**, and recommended a multi-year program to implement the models, establish and maintain a data archive, apply the models to specific situations of interest, answer generic questions, compare outputs with observations, identify potential problem areas, and, if necessary, design a field study for model verification.

4.2.3 Long Range (Greater than 1000 km)

As part of Western Canada acid deposition monitoring activities, the Atmospheric Environment Service of Environment Canada applied their long-range transport model to the impact of Western North America sources upon several Alberta sites (Kociuba et al. 1984). Wet deposition of sulphur in Alberta was found to be 1 to 2 $kg \cdot ha^{-1} \cdot yr^{-1}$, of which about 60% was due to the assumed background. The predicted values were all smaller than those observed. Total deposition at Alberta sites ranged from 2.1 to 6.7 $kg \cdot ha^{-1} \cdot yr^{-1}$, the wet component accounting for 23% of the larger figure and 51% of the smaller figure.

5. SUMMARY

For sound environmental management, the integration of measurements, monitoring data, and modelling forecasts is essential. Fragmented information from Alberta research studies and monitoring programs has become available over the years, but integrated studies such as the Acid Deposition Research Program are needed. Models used to predict air quality and deposition in Alberta have yielded somewhat different results which have not been verified (due to the paucity of appropriate measurements and monitoring data). A unified data base is required to apply and test available models. Existing atmospheric models need to incorporate mesoscale processes and be linked to environmental response models. Further measurements of the atmospheric concentration and deposition velocities are required to determine the amount of dry deposition of gases and aerosols. The contribution of windblown dust to total deposition is presently unknown. Measurement, monitoring, and modelling of atmospheric pollutants will assist in both the development of deposition standards/guidelines and their attainment.

Table 4. Models selected for use in Alberta and Western Canada.

	Mathematical Frame of Reference	
Application Type	Lagrangian	Eulerian
Urban photochemical	PLMSTAR	AIRSHED
Mesoscale deposition	MESOPUFF II	RTM III
Advanced complex		ADOM
Statistical	OME-STATMOD	FISHER RCDM

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AN ANALYSIS OF NUMERICAL MODELS OF AIR POLLUTANT EXPOSURE AND VEGETATION RESPONSE

by

S. Krupa,[1] R.N. Kickert,[2] and M. Nosal[3]

ABSTRACT

A number of empirical (statistical, regression-oriented) and mechanistic (process-oriented) models are presently available to examine the relationship between air pollution stress and plant response. These models have their strengths and weaknesses. In all these models, a major concern is the numerical definition of the pollutant exposure kinetics (dose). At present, there are no numerical definitions of dose which make satisfactory biological sense. A key issue is the existence of a biological time clock where plants respond differently to the pollutant stress at different stages of their growth. On the other hand, policy makers and regulatory personnel prefer a simple approach which would facilitate implementation and administration of ambient air quality standards.

Air pollutant averaging techniques create artifacts due to the non-normal distribution of ambient concentrations. A more appropriate approach may be the use of 'median' and 'percentiles.'

Any transfer of results from unit level models to regional level leads to 'scaling error.' There is no general agreement among researchers on how to deal with the scale problem. While this situation persists, any policy formulated on regional impact assessment must acknowledge the uncertainty.

[1] Department of Plant Pathology,
University of Minnesota, St. Paul, MN
[2] Consultant; 4151 N.W. Jasmine Place, Corvallis, OR
[3] Department of Statistics and Applied Mathematics
The University of Calgary, Calgary, AB

1. INTRODUCTION

A model can be described as information, data, principles, etc., arranged or grouped, usually mathematically, so as to represent or describe a certain idea or a condition. In evaluating the impacts of air pollutants on cultivated and native vegetation, a number of investigators have proposed empirical (statistical, regression-oriented) and mechanistic (process-oriented) models (Heck et al. 1984a, b; Kercher 1980; Kercher and Axelrod 1984; King et al. 1983; Nosal 1983; Oshima et al. 1976; Shugart et al. 1980; Stevens and Hazelton 1976). These and other similar models have attempted to explain the relationship between acute (short-term, high pollutant concentration) or chronic (long-term, low pollutant concentration, with periodic, intermittent episodes or peaks) exposure and plant response. Depending on the timing of the stress, whole plants can frequently recover from the effects induced by an acute exposure in one part of the plant through compensatory processes. On the other hand, of greater concern are the effects which result from long-term chronic exposures. Such chronic effects consist of changes in growth, productivity, reproduction, and quality, including features relevant to aesthetic and recreational aspects.

There are a number of uncertainties attached to the assessment of air pollutant-induced ecological effects. However, uncertainty is an accepted phenomenon when modelling biological systems. This uncertainty arises from the stochastic nature of many biological stimulus-response relationships and is a reflection of the inherent stochasticity of both the biological system itself and the environment that drives that system . . . (this) makes it almost impossible to predict a response that is deterministic, i.e., without variation (Krupa and Teng 1982).

Within the context of the actual investigation, uncertainties originate from errors in: (1) monitoring the air quality; (2) experimental and numerical definition of the pollutant exposure kinetics; (3) experimental design to characterize the cause and effects relationships; and (4) modelling the pollutant-response relationships.

2. THE CONCEPT OF DOSE

'Dose' is one of the most frequently used terms in air pollution-vegetation effects literature. Dose can be defined as the exact amount or extent of a given treatment to which a given receptor is subjected at one time or at stated intervals. The numerical expression of dose is an area of much controversy at this time.

Historically, dose has been expressed as pollutant concentration (c) times duration of exposure (t), or as an average of pollutant concentration over exposure duration (c/t) (refer to "Effects of SO_2 and its Derivatives on Health and Ecology", International Electric Research Exchange 1981). More recently, it has also been expressed as integrated exposure (IE), determined by summing the product of concentration times the total exposure period when the pollutant concentration exceeded a set, minimum threshold (Lefohn and Benedict 1982).

In the numerical definition of dose, several considerations are critical, both in regard to the cause (air pollutant) and the receptor (vegetation) response. Air pollutant averaging techniques assume normal distribution of ambient pollutant concentrations. However, in reality the distributions of ambient ozone (O_3) and sulphur dioxide (SO_2) concentrations are best described by Weibull and gamma functions (Nosal in press). A consequence of these non-normal distributions on the application of pollutant averaging techniques, for example, is illustrated by the studies of Hogsett et al. (1985). In this study, two exposure regimes were used to compare a set of episodic ozone exposure patterns with daily exposures. An episodic ozone pattern, applied to alfalfa over a 133-day growth period, elicited a greater growth response compared to a daily peak exposure pattern. The two profiles had similar integrated exposure values but different 7-h seasonal means. The 7-h (0900 to 1559 h) means for the two profiles were inversely correlated with the observed growth response. The episodic profile had a smaller seasonal mean and yet caused a greater yield reduction.

Another example of the artifacts induced by pollutant averaging techniques pertains to SO_2 concentrations downwind from a large point source in Minnesota (Krupa and Gardner in prep.). Ambient ground level SO_2 concentrations were monitored continuously over a 10-yr period at seven locations relative to the source plume dispersion. When hourly pollutant averages were examined, during 90% of the monitored period, SO_2 concentrations were reported to be zero. However, when the continuous data were examined, within the 90% time there were numerous instances (>50% cases) when the plants were exposed to SO_2 concentrations as high as 0.50 ppm for 5 min. Even though in this particular case no negative effects have been observed, it is important to note that it is well accepted that chronic effects are the result of the cumulative impact of intermittent episodes. Such a cumulative impact is not a straightforward additive function, since the final biological response is a product of the stress minus the ability of the plants to compensate. This brings forth the concept of frequency of occurrence of pollutant episodes and the time interval between such episodes. During the time interval between episodes, gaseous pollutants can and do exist in low concentrations. Exposure of plants to such low pollutant concentrations either can predispose them to subsequent episodes or confer tolerance (Godzik and Krupa 1982).

From the perspective of receptor (vegetation) response, plant physiologists and plant pathologists have clearly shown the importance of plant growth stage in the end response of vegetation to biotic or abiotic stress (Benson et al. 1982; Teng and Gaunt 1980). This brings forth the concept of biological time clock and stress (Figure 1). For example, defoliation or foliar injury to soybean by hail during the early part of the plant growth would have no effect on the final yield. Conversely, such a stress during flower set to pod filling would result in significant yield loss (Lockwood et al. 1977).

Thus, a satisfactory numerical expression of dose should consider:

1. The artifacts of pollutant averaging techniques;
2. The episodicity of pollutant occurrence and exposure;
3. The time intervals between episodes; and
4. The relationship between the pollutant stress and the biological time clock (growth stage).

According to Runeckles and Brown (in prep.), one model which does not provide a simple dose statistic but which minimizes the uncertainties of overall dose-response is that of Nosal (1983). This model accounts for the number of pollutant episodes, highest peak pollutant concentration, and the cumulative numerical integral (concentration over time) of the exposure. The weakness of this model, however, is that it does not provide a complete numerical explanation of the importance of the individual episodes or its relationship to the biological time clock. However, it considers the concept

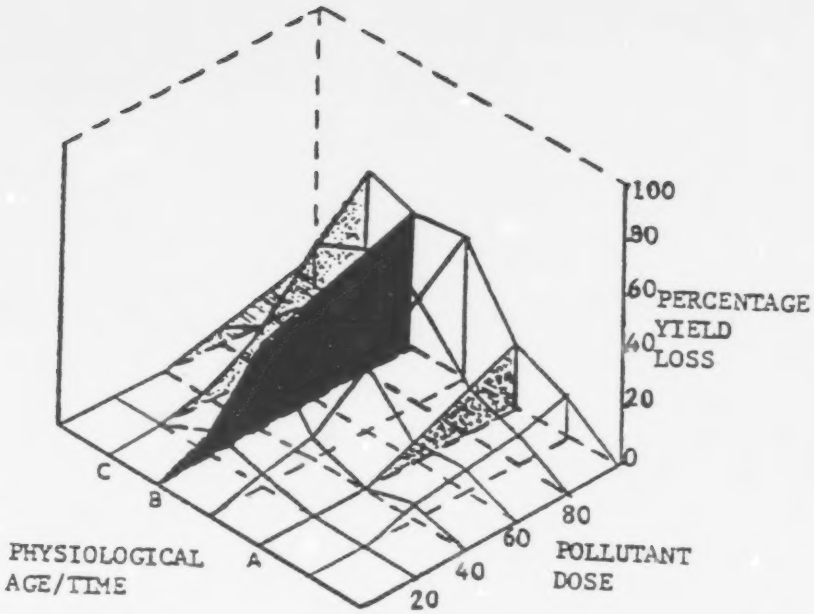
100
80
60 PERCENTAGE
YIELD
40 LOSS
20
0
C
B
A
PHYSIOLOGICAL
AGE/TIME
80
60
40
20
POLLUTANT
DOSE

Figure 1. Conceptualization of the response surface of yield loss to pollutant dose as influenced by crop development stage (after Teng and Gaunt 1980 and Krupa and Teng 1982).

of episodicity and fluctuations in ambient air quality over time with response rather than attempting to define a dose statistic.

While the previous narrative pertains to gaseous air pollutants, significant attention has been directed in the recent years to the phenomenon of 'acid rain' (U.S. National Research Council 1983). A number of investigators have used linear or linearizable statistical regression techniques in defining the temporal and spatial aspects of rainfall chemistry to which vegetation is exposed. Recently, Nosal and Krupa (in press) showed that the treatment of data by linear or linearizable regression methods violates the assumptions required for the use of such techniques (namely, normal distribution of data, normal distribution of the residuals in the regression, homoscedasticity, equal dispersion, unbias or mean zero, and independence). Such data also fail to qualify under 'robust regression.' These considerations are very critical, since almost all studies on the impact of acid rain on vegetation relate to simulation experiments which are based on the assumptions found to be violated by Nosal and Krupa (in press).

This overall discussion points out the difficulties, artifacts, and errors associated with the numerical description of dose. Unfortunately, in the real world, the vegetation is subjected to stress differently. Any description of dose must make biological and statistical sense. If the two requirements can be achieved simultaneously, such an output would be a desirable solution to the problem.

One aspect of dose which has not been considered is the question of 'exposure dose' versus 'effective dose.' Exposure dose may be defined as the pollutant regime to which the plant species is exposed as defined by appropriate ambient measurements. Effective dose may be defined as the actual quantity and rate of the pollutant which is absorbed by the plant. It is the effective dose that results in the observed or measured effect. However, since the numerical definition of exposure dose itself is an area of much controversy, no effort is made here to examine the details of effective dose.

3. AIR POLLUTANT-VEGETATION RESPONSE MODELS

In spite of the difficulties pointed out regarding the numerical description of pollutant dose (exposure kinetics), a number of investigators have developed empirical (Tables 1 and 2) and mechanistic (Tables 3 and 4) models to relate pollutant-plant response relationships. It is beyond the scope of this paper to describe all these models and, for the details, the reader is referred to Krupa and Kickert (in prep.). In the following sections, an analysis of an example for each of the two types of models is provided. No special criteria were used in selecting the two examples.

3.1 EMPIRICAL MODEL

An example of an empirical model is that of Heck et al. (1982). Their model considered statistical regression between O_3 concentration and crop loss as:

1. Simple linear regression

$$y = b_0 + b_1 X$$

where:

y = yield as grams per plant
X = mean O_3 concentration

2. Plateau-linear model

$$y = b_0, \text{ if } X \leq \theta$$

$$y = (b_0 - b_1 \theta) + b_1 X, \text{ if } X \geq \theta$$

3. Percent yield reduction model

$$y = \frac{100b_1}{a} [0.025 - X]$$

In this study:

1. Most regression scattergrams have only five or six points (corresponding to different treatments). The fitting is done using models with two (Model 1) or three (Model 2) parameters. It follows from statistical theory that a high R^2 value, as reported in the paper, does not necessarily reflect a high degree of fit of the model, but is a logical (not empirical) consequence of limited experimental design. Sparse data (five points) are over-parameterized by a three-parameter model and good fit is theoretically guaranteed.
2. In the experiment of Heck et al. (1982), O_3 concentrations among several treatments differed only by a constant value

Table 1. Air pollutant-plant response, empirical (statistical) models.

No.	Reference	Vegetation/Plant Time Frame	Air Pollutant(s)	Plant Production Response Properties	Air Pollutant Exposure Properties	Other Limits to Growth	Main Biological Paradigm
1.	Nosal 1983	soybean chronic	SO_2, O_3	Number of pods/plant. Seed weight/plant. Number of seeds/plant. Weight of 1000 seeds.	Number of pollutant episodes Cumulative concentration for duration of all episodes (ppb) Peak concentration (ppb)	None	Crop yield responses are assumed to be statistically associated with pollutant regime properties.
2.	Nosal in press	northern coniferous forest chronic	SO_2	Annual basal area growth increment for lodgepole pine trees.	Same as above	None specified	Pine tree growth is assumed to be statistically associated with pollutant regime properties.
3.	Fox et al. in press	western larch trees chronic	SO_2	Annual tree trunk radial growth.	Smelter emissions of sulphur (tons/year)	Precipitation	Tree ring width series away from the affected tree locations are assumed to represent macroclimatic effects on annual tree ring growth. Deviations for trees near sulphur-emitting smelters are assumed caused by exposure to sulphur in the air.
4.	Benson et al. 1982	alfalfa acute and chronic corn, wheat, potatoes chronic	O_3	Loss in foliar and stem alfalfa biomass weight. Seasonal yield loss for corn in wt./100 kernels; for wheat in wt./100 seeds; and for potatoes in tuber wt./plant.	Sum of hourly average concentration per day ($ppb \cdot d^{-1}$) Accumulative sums of hourly average concentrations for weekly periods over the entire season ($ppb \cdot h^{-1}$)	None specified	Exposure to pollutant results in uptake by the crop and is the sole cause of reduction in production of merchantable parts.
5.	Heagle et al. 1986	soybean chronic	O_3	Foliar injury percent. Filled pod field density. Filled pod weight. Seed weight. 100 seed weight.	7-h daily seasonal mean (ppm)	None specified	Crop yield change is related to O_3 concentration over the growing season but processes are not modelled.

Continued...

Table 1. Concluded.

No.	Reference	Vegetation/Plant Time Frame	Air Pollutant(s)	Plant Production Response Properties	Air Pollutant Exposure Properties	Other Limits to Growth	Main Biological Paradigm
6.	Heck et al. 1984a,b	wheat, barley, sorghum, corn, soybean, peanut, kidney bean, cotton, tomato chronic	O_3	Seasonal percent change in: wheat, sorghum, corn, soybean and kidney bean seed yield ($kg \cdot ha^{-1}$); barley seed weight/head; peanut pod weight/ha; cotton lint and seed weight/ha; tomato fresh weight/plot.	7-h daily seasonal mean concentration (ppm)	None	Crop yield change is related to O_3 concentration over growing season, but processes describing how are not given.
7.	Heck et al. 1982	soybean, lettuce, peanut, turnip, kidney bean chronic	O_3	Dry weight of soybean seed per plant; fresh weight of lettuce head/plant; peanut pod weight/plant; edible turnip root fresh weight/plant; kidney bean dry weight/plant.	7-h daily seasonal mean concentration (pphm)	None	(Same as above)
8.	Larson and Heck 1976	various grains, vegetables, tobacco and ornamental flowers and deciduous trees	O_3, SO_2	Leaf injury symptoms.	Pollutant concentration (ppm) Geometric mean pollutant concentration for 1 h (ppm)	None	Different levels of pollutant concentration and exposure duration can compensate to produce similar levels of leaf injury.
9.	Loehman and Wilkinson 1983	soybean, wheat corn chronic	O_3	Crop yield per plant for corn and soybean; seed weight/plant for wheat.	7-h daily continuous concentration (ppm)	None	Exposure to pollutant results in uptake by the crop and is the sole cause of reduction in production of merchantable parts.
10.	Medeiros et al. 1983	soybean chronic	oxidants acid precipitation	Bushels of soybean/acre.	Hydrogen ion concentration in precipitation ($mol \cdot L^{-1}$) 7-h daily mean oxident concentration (pphm).	Heat (maturity zone) relative humidity	Mixtures of pollutants and other environmental conditions affect crop yields.

Table 2. Air pollutant-plant response, empirical (statistical) models.

No.	Reference	Field Application Results	Sensitivity Analysis Results	Mathematical Nature		Computer Memory	Computer Language	Model Documentation
				Exposure	Plant Response			
1.	Nosal 1983	No development of independent field tests available for soybean.	R^2 regression values given for various plant responses to various pollutant concentrations; all $R^2 > 0.85$.	Mulitvariate polynomial Fourier equation involving the three exposure properties.	First-order non-linear polynomial regression equation for the plant response variable.	IBM/XT	APL PLUS	Resulting regression equations with statistics given; program code not published; system flowchart not relevant to approach and not given.
2.	Nosal in prep.	No development of independent field tests available for other forest plots.	R^2 regression values given for five locations at varying distances from emission source.	Multivariate polynomial Fourier equation involving the three exposure properties.	First-order non-linear polynomial regression equation for the plant response variable.	IBM/XT	APL PLUS	Same as above
3.	Fox et al. in press	Not applied independent of sites used to develop.	Some scattered evidence.	Single multivariate linear regression equation with tree growth a function of sulphur emission.		?	?	General form of single statistical regression equation only.
4.	Benson et al. 1982	Applied statewide but not field checked for validity of estimated losses.	R^2 regression values: corn (0.876) potato (0.929) wheat (0.949) alfalfa (0.131 to 0.999)	Single non-linear polynomial equation for alfalfa. Single multitvariate (weekly periods) linear equation for corn, wheat, potato.		?	FORTRAN	Statistical equations given; no computer programs published.
5.	Heagle et al. 1986	Field data used for model definition only.	Standard errors for parameters are generally lower for Weibull model than polynomial forms.	Various forms of non-linear Weibull model and polynomial models are used.		?	?	Mathematical equations given with parameter values.
6.	Heck et al. 1984a,b	Uses exposure and crop yield field data (open top chambers) for model development,but not clear whether other data used to test models.	Relative yield losses for each crop at four seasonal 7-h daily mean ozone concentrations are given.	Non-linear Weibull model used to relate observed crop yield to an O_3 exposure statistic; relative yield change is computed by yield differences under background and elevated O_3 concentration, divided by yield under background concentration.		?	requires statistical analysis program, but not specified.	Crop yield equation given with table of parameter values by crop, cultivar, date and location (but applicability to other locations and years is open question).

Continued...

Table 2. Concluded.

No.	Reference	Field Application Results	Sensitivity Analysis Results	Mathematical Nature		Computer Memory	Computer Language	Model Documentation
				Exposure	Plant Response			
7.	Heck et al. 1982	Not tested independently to other locations.	R^2 values for linear relations of yield to O_3 range from 0.65 to 0.996; R^2 values for plateau linear relations range from 0.94 to 0.99.	For crop yield as a function of seasonal 7-h/day mean O_3 concentration: - a simple linear equation - plateau-linear equation Percent crop yield reduction is a linear function of exposure statistic exceeding background.		NA	NA	Tables of parameter values are given for all models and crops considered.
8.	Larson and Heck 1976	Not tested independently in field.	Multiple correlation coefficients are given.	Multivariate non-linear equation expressed as type of power function.		NA	NA	Equation and table of parameter values by crop are given.
9.	Loehman and Wilkinson 1983	Not tested independently in field.	None	Single linear equation for soybean yield reduction with cultivar-dependent rate; non-linear quadratic equation for corn and wheat yield reduction.		NA	NA	Equations given for each crop.
10.	Medeiros et al. 1983	Applied to other field studies only having one of the two exposure statistics; expected yield gains with control are 2x to 5x greater with only one pollutant.	Limited to field application results. (See column to left.)	Linear and non-linear regression equations for yield as a function of both hydrogen ion concentration and oxidant.		NA	NA	Equations given along with error statistics.

NA = Not Applicable

Table 3. Air pollutant-plant response, mechanistic (process) models.

No.	Reference	Vegetation/Plant Time Frame	Air Pollutant(s)	Plant Production Response Properties	Air Pollutant Exposure Properties	Other Limits to Growth	Main Biological Paradigm
1.	Kercher 1980	sugarbeet and various annual crops acute and chronic	SO_2, H_2S	Gross and net photosynthesis. Foliage biomass. Stem biomass. Fruit biomass. Root biomass.	Pollutant concentration in air, continuous (ppm)	Light, heat, CO_2, precipitation, wind	Physiological model of crop photosynthesis, allocation to plant parts for growth and yield over season under air pollutant with a threshold effect on photosynthesis.
2.	Coughenour 1981	western wheatgrass rangeland chronic	SO_2	Forage biomass. Forage N and S content (quality).	Continuous, constant concentration ($\mu g \cdot c^{-3}$)	Light, heat, wind, moisture, available nitrogen and sulphur	Detailed physiological processes of S uptake by leaves and roots, and movement between plant parts.
3.	Heasley et al. 1981	shortgrass prairie chronic	SO_2	Live plant weight above ground. Shoot S content.	3-h average SO_2 concentration at US federal standard level (ppm)	Light, heat, precipitation, relative humidity, wind	Carbon, N, S cycling through ecosystem consisting of physical processes, vegetation, soil, and ruminant animals.
4.	Kercher et al. 1980; Kercher and Axelrod 1981	conifer forest chronic	SO_2	Growth and survival of trees by species. Basal area of tree stems by species.	Two options: SO_2 averaged over season or accumulated dose (ppm) Log of accumulation dose from successive episodes	Light, heat, moisture stress based on evapotranspiration, fire	Dominance of a tree species in community is a result of competition caused by changes in species-dependent growth rate of individuals.
5.	Luxmoore 1980	oak-hickory deciduous forest acute and chronic	SO_2 zinc, lead	Plant tissue growth effect related to tissue pollutant concentration (accumulation).	Pollutant concentration in air ($\mu g \cdot mL^{-1}$) Foliar uptake of particle deposition ($g \cdot m^{-2}$ land) Foliar uptake of gases by diffusion, controlled by resistances ($\mu g \cdot mL^{-1}$)	CO_2, light, moisture	Part of five complex interrelated models of carbon flow, biomass accumulation and transfer, water flow and soil chemistry-solute flow through plant physiological processes.
6.	King et el. 1983	soybean chronic	O_3	Soybean yield intended but only O_3 uptake is given in paper.	Mean hourly O_3 concentration (pphm).	Light, heat, soil, water potential	

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Table 3. Continued.

No.	Reference	Vegetation/Plant Time Frame	Air Pollutant(s)	Plant Production Response Properties	Air Pollutant Exposure Properties	Other Limits to Growth	Main Biological Paradigm
7.	Miller et al. 1982	western mixed conifer forest chronic	O_3	Tree photosynthesis. Tree foliar biomass. Foliar litterfall. Tree diameter growth. Tree mortality, cone/seed production, seedling survival. Forest tree species composition. Dead tree fuel load.	Hourly average ozone concentration (pphm-h)	Heat, moisture, tree diseases, insect pests	Photosynthesis of pines, population dynamics of trees as affected by physical growth resources, O_3 disease and insects.
8.	Ares 1979	coastal desert shrub steppe chronic	fluorides	Carbon in leaves. Fluoride in leaves.	Average daily ambient fluoride concentration ($mg{\cdot}m^{-3}$)	Light, heat, rain, wind	Mass balance of fluoride in vegetation and soil over growing season.
9.	Mortenson 1984	winter and spring cereals, legume crops, potato, sugarbeet, fodder beet, oil seed crops, grass, vegetables chronic	sulphate, nitrate, cadmium, calcium, potassium, magnesium, sodium, ammonium	Ion concentration in harvested crop. pH in upper soil under crop.	Pollution concentration in air ($\mu g{\cdot}m^{-3}$) Deposition (annual) (for parent and daughter products) ($g{\cdot}m^{-2}$)	None; growth is constant by month and crop type	Mainly a soil chemistry budget model where crops are sinks for various ions in transit.
10.	Harwell and Weinstein 1983	eastern deciduous forest chronic	SO_2, O_3, NO_x	Annual productivity of forest stand.	Average annual pollutant load	Light, heat, moisture, nutrients	Individual tree growth in a stand is determined by physical resources needed, after Weinstein 1982, Shugart and West 1977, and Botkin et al. 1972.
11.	Harwell and Weinstein 1983	acute	SO_2, O_3, NO_x	Percent change in fixed carbon partitioning. Annual diameter growth.	Mean daily pollutant concentration	Light, heat, moisture, nutrients	Hourly/daily photosynthesis simulation (details not documented)
12	Andersson et al. 1980	Scots pine forest chronic	acid precipitation	Annual wood production and N content.	Nitrogen as wet deposition ($kg\ N{\cdot}ha^{-1}{\cdot}yr^{-1}$)	None	Assumes acid deposition alters processes of N transformation in N cycle and tree growth changes as a result.

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Table 3. Concluded.

No.	Reference	Vegetation/Plant Time Frame	Air Pollutant(s)	Plant Production Response Properties	Air Pollutant Exposure Properties	Other Limits to Growth	Main Biological Paradigm
13.	Haines and Waide 1980	eastern deciduous forest chronic	acid precipitation	Nitrogen in tree stems	Constant pH of rain for 1 $h \cdot wk^{-1}$	None described	Mass balance N budget for hardwood trees, herbivores, woody litter, soil, soil microbiota, and meteorological wet and dry deposition.
14.	West et al. 1980	eastern deciduous forest chronic	not explicitly used	Total tree biomass by species	Not explicitly modelled	Light, heat, soil litter	Diameter and height growth of single trees among a mix of species each competing for different resource requirements for growth.

Table 4. Air pollutant-plant response, mechanistic (process) models.

No.	Reference	Field Application Results	Sensitivity Analysis Results	Mathematical Nature		Computer Memory	Computer Language	Model Documentation
				Exposure	Plant Response			
1.	Kercher 1980	No independent field tests aside from data used to parameterize model.	Not comprehensive; only CO_2 uptake versus H_2S and CO_2 concentration in air.	'Instantaneous' concentration of gaseous pollutant in linear and non-linear diffusion equations according to concentration and plant's threshold.	Net photosynthesis is depressed linearly above threshold, and increased quadratically below threshold in foliar diffusion.	?	?	System flowchart and mathematical equations are in Kercher 1977; program code not published.
2.	Coughenour 1981	Grass shoot S for season from model closely matched field observations.	SO_2 deposition rate is sensitive to concentration, forage amount, and soil water content; forage S content is sensitive to change in long-term SO_2 ambient concentration.	Linear equation for concentration diffusion resistance flow rate modified by leaf area index into leaves; root uptake of sulfate as Michaelis-Menton kinetics.	S transferred to plant parts by seasonal changes in shoot;root ratio for S/C.	?	SIMPCOMP	System flowchart and mathematical equations for biological and environmental processes, but no computer code published.
3.	Heasley et al. 1981	Soil moisture, plant weight, and shoot S content over two seasons showed good match between predicted and observed.	Over 31-year period elimination of SO_2 revealed low sensitivity of all ecosystem components; inorganic S pool is relatively most sensitive.	Steady state Gaussian plume model used to generate 3-h average SO_2 concentration.	SO_2 deposition in canopy by diffusion resistance flow into foliage; finite difference equations for flows of C, N, S through ecosystem.	?	FORTRAN	Gives system flowchart, but no mathematical equations for model.
4.	Kercher et al. 1980 Kercher and Axelrod 1981	Unknown for air pollution conditions, but performance appears realistic and reasonable under non-pollution conditions.	See Kercher and Axelrod 1984.	Simple seasonal average (accumulated dose) or episodal accumulations only.	Tree growth effect is patterned after empirical dose-response method of Larson and Heck 1976.	?	FORTRAN	Computer flowchart in Kercher and Axelrod 1984. Complete description in Axelrod and Kercher 1981.
5.	Luxmoore 1980	Applied to a field situation but not compared to independent field data.	Selectively; not comprehensive.	Non-linear gaseous diffusion equation for foliar uptake and cuticular conduction of particulates.	Simple generic ramp function used to relate growth effect to tissue elemental concentrations.	?	?	See Luxmoore et al. 1978 general system flowchart; computer programs not published; complete mathematics not published.

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Table 4. Continued.

No.	Reference	Field Application Results	Sensitivity Analysis Results	Mathematical Nature		Computer Memory	Computer Language	Model Documentation
				Exposure	Plant Response			
6.	King et al. 1983	None reported in this initial paper.	Daily O_3 uptake versus soil water potential, light, temperature.	Accumulated O_3 gas diffusion into foliage over a day.	Photosynthesis and O_3 uptake respond to diurnal temperature and moisture stress in a complex set of equations.	?	FORTRAN	?
7.	Miller et al. 1982	Not done, mathematical models not completed.	Not done, mathematical models not completed.	Not done, project terminated prior to completion.	See Harwell and Weinstein 1983 (above).	NA	NA	See references in Miller et al. 1982; system flowchart; some sub-models have mathematics documented.
8.	Ares 1979	Development not to this stage.	Development not to this stage.	No mathematical equations given.	No mathematical equations given.	?	?	System flowchart and word model description only.
9.	Mortensen 1984	Not yet available.	Limited preliminary results in Christensen et al. 1985 for pH and cadmium in soil.	Root uptake proportional to water uptake and ion concentration in interstitial water on a monthly basis. Uptake from air through dry and wet deposition is a non-linear equation; uptake proportional to total deposition and vegetation interception fraction.	Non-linear algebraic equations for biomass, ion uptake, flows, and ion concentrations in crops.	B7800	FORTRAN	Mathematical equations and tables of coefficients; sample printouts in Christensen et al. 1985; no flowcharts; program code not published.
10.	Harwell and Weinstein 1983	Development not to this stage.	Development not to this stage.	Selected by probability from a historical frequency distribution.	Individual tree diameter growth is a second order function of maximum diameter and height for the species multiplicatively altered by availability of resources for growth.	?	?	?

Continued...

Table 4. Concluded.

No.	Reference	Field Application Results	Sensitivity Analysis Results	Mathematical Nature		Computer Memory	Computer Language	Model Documentation
				Exposure	Plant Response			
11.	Harwell and Weinstein 1983	Development not to this stage.	Development not to this stage.	No description for how the annual pollutant load is obtained from frequency distribution of mean daily concentrations.	Not documented.	?	?	Only an incomplete preliminary design paper was available for this review; no flowcharts.
12.	Andersson et al. 1980	Development not to this stage.	Annual wood production is more sensitive to precipitation of N than of other N cycling processes.	Not explicitly modelled.	All N flows are linear equations.	NA	NA	System flowchart and parameter values given; equations can be constructed from these.
13.	Haines and Waide 1980	Static budget model not suitable for field application except for location where developed.	Not available.	Entered as increased ammonia and nitrate N into system from precipitation.	Root N content is a funcion of ammonia and nitrate N uptake as linear finite difference equations.	?	?	System flowcharts in Mitchell et al. 1975; set of finite difference equations not shown but can be written from flowchart; computer code not published.
14.	West et al. 1980	A prior model version was compared with/without American chestnut to historical records.	Total biomass by tree species in mixed species forest can be more or less than growth rate reduction implies because of competition effects.	Not explicitly modelled.	Tree species' sensitivities to visible leaf injury used to set constant loss of growth of either 0, 10, or 20% in non-linear difference equations.	IBM mainframe	FORTRAN	Computer program flowchart and mathematics in Shugart and West 1977; computer program in Botkin et al. 1970.

during the whole experiment. This is contrary to the episodic nature of O_3 concentrations and their spatial variability under ambient conditions. Hence, the results may be theoretically interesting but their applicability to field conditions is questionable. In reality, one should consider dynamic air pollutant flux experiments, for example, as described by Nystrom et al. (1982).

To alleviate the aforementioned criticisms, scientists at the University of Minnesota are conducting a study to evaluate alfalfa responses to chronic, ambient SO_2 exposures, consisting of 54 treatments. This approach corrects for the statistical over-parameterization problem and, in addition, provides significantly variable and not constant differences between the treatments.

3.2 MECHANISTIC MODEL

An example of a mechanistic model is that of Kercher (1978). This is a simple model for the change of photosynthetic capacity (F) caused by an air pollutant acting on that component, with a turnover time (d^{-1}):

$$\frac{dF}{dt} = B(I,E) - (d - I)F \qquad \text{(a)}$$

where:

F = factor multiplying leaf photosynthesis
I = internal concentration of phytoactive agent
B = regeneration rate of F
E = available energy for regeneration

The function B and rate d are hard to measure. For small turnover and repair rates and chronic exposures, a simple approximate solution to Equation (a) is given by:

$$F = 1 - a \int_0^t I\,dt \qquad \text{(b)}$$

where:

a = constant determined by photosynthesis measurements
I = internal concentration of phytoactive agent

Assuming that the internal loss of the toxic agent is proportional to its concentration and the agent is replenished by diffusion into the leaf, then Equation (b) may be rewritten as:

$$F = 1 - a^1 \int_0^t \frac{[O_3(t)]}{r(t) + b}\, dt \qquad (c)$$

where:

r = sum of resistance to O_3 diffusion

$[O_3]$ = external ozone concentration, which is time dependent

a^1; b = constants determined from photosynthesis measurements

Equation (c) was derived to estimate the cumulative effects of pollution as opposed to the effects of acute exposures (non-linear dose-response relationships). If repair mechanisms or alternative modes of loss of the toxic agent are invoked, then Equation (c) is supposed to be replaced by one with a threshold. As previously stated, the use of a threshold does not account for pre-disposition or tolerance to subsequent episodes. What is more interesting is that the model was tested to a limited degree with only results of studies such as that of Heck et al. (as reported by King et al. 1983).

4. DISCUSSION

Both empirical and mechanistic models have their strengths and weaknesses. The experimental and modelling steps in an impact assessment program are closely related since the data collected often dictate the type of model that can be developed or applied, while specifying the use of a given model at the outset will influence the experimentation. In air pollution research, it is common to find these two steps treated separately and even conducted by different researchers, a situation that invariably leads to confusion and conflict between the biological validity of a model and its mathematical representation.

In Figure 1, a conceptual representation, short-term, acute exposures enable the development of models, represented by a response plane, while long-term, chronic exposures enable the development of models represented by a surface spanning several response planes. Each response plane depicts the potential impact of air pollution at defined plant development stages and response planes will differ in shape because physiologically, for example, a crop will show differential response to a set or similar exposure at different periods of its life. Much of the published literature on air pollutant impacts on agriculture has not been able to account for this differential response, with scientists simplifying biology by developing a whole season dose-response statistic. In regression analysis, using published data supplied by the original researchers, at least one study (Benson et al. 1982) has shown that potentially more meaningful impact is assessed using models that recognize the relative importance of growth stages. Many air pollutants occur in a stochastic manner, and it is questionable whether whole season dose-response functions that are so commonly used have any interpretive value. The policy makers and regulatory personnel prefer a simple approach which would facilitate implementation and administration of ambient air quality standards. Mathematical artifacts introduced through the computation of seasonal dose or through averaging techniques, as described previously, do not make much biological sense. Perhaps an approach which could be meaningful consists of the use of the median and the percentiles.

Ecological effects assessed using either of the two group of models defined in this paper will have a degree of uncertainty associated with the quality of data used in the modelling. Empirical-regression models are mainly plot-level models, while explanatory-simulation models are mainly process-level models. In the strictest sense, a model is only applicable at the level from which it is derived, yet we are often forced to make impact assessments at the regional level. This possibility of incurring a scale error is one of the most critical issues facing air pollution researchers on how to deal with the scale problem, and while this situation persists, any policy formulated on regional impact assessment must acknowledge the uncertainty.

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AIR POLLUTION MEASUREMENT AND EFFECTS RESEARCH: A PERSPECTIVE ON AGRICULTURE AND FORESTS

by

H.C. Jones,[1] Frances P. Weatherford,[1] J.C. Noggle,[2]
and Charlie McDuffie, Jr.[2]

ABSTRACT

The Tennessee Valley Authority experience with air pollution emissions from its 12 coal-fired power plants as they relate to impacts on ambient air quality and acute and chronic effects on vegetation is reviewed. All plants are in compliance with all state and federal air quality regulations.

Ambient monitoring data show that for worst case conditions, a conservative estimate of the maximum total exposure for any given location to hourly sulphur dioxide (SO_2) levels in excess of 153 $\mu g \cdot m^{-3}$ would be less than 2% of the daylight hours during a 6-mo growing season. Exposures were intermittent and averaged 1.5 h in duration. Total exposure during the growing season was approximately 45 to 50 h. Data for 40 000 records of SO_2 concentrations and associated inspections of vegetation for visible injury indicated that there were only 4 chances in 100 for occurrences of effects at 1330 $\mu g \cdot m^{-3}$, 1-h average, unless the associated instantaneous peak concentrations exceeded 2600 $\mu g \cdot m^{-3}$. Based on comparisons of emission rates, ambient air concentrations, and observations for effects, it is concluded that there is little, if any, chance of occurrences of visible foliar injury where emission rates do not exceed 1.2 lb $SO_2 \cdot 10^{-6}$ Btu. With respect to the effects of chronic exposure to SO_2, acid rain, or mixtures of SO_2 and other pollutants, the data are too meager to draw firm conclusions. Few experiments have been conducted under ambient conditions or under laboratory conditions that adequately simulate ambient exposures. Tennessee Valley Authority researchers have been unable to detect adverse effects of chronic exposure on the SO_2 sensitive soybean cultivar, Essex, under either ambient or simulated exposure regimes. However, during the same experiments, significant reductions in yields attributable to regional levels of ozone were measured.

[1] Tennessee Valley Authority, Knoxville, TN
[2] Tennessee Valley Authority, Muscle Shoals, AL

1. INTRODUCTION

The practical application of air pollution measurement and effects research is the evaluation of existing air pollution impacts, and the assessment (or prediction) of impacts of any given change in air quality resulting from decreases or increases in resultant emissions. This requires that we know what the pollutants are, their ambient concentrations, their emissions, and their effects on the environment. In our case, we are concerned with the effects on agriculture and forests. While our remarks will be limited to our experiences around large coal-fired power plants, they are generally applicable to other point sources of sulphur dioxide (SO_2). Similarly, while much of our discussion deals with effects of gaseous pollutants on crops, the issues are applicable to forests and to the secondary acid particulate pollutants derived from the acid gases.

2. ACID-FORMING POLLUTANTS

The acid-forming pollutants we are most concerned with are sulphur oxides, nitrogen oxides (which are only now receiving the attention they deserve), and carbon dioxide, all of which occur naturally and are being emitted in the combustion of fossil fuels. Carbon dioxide (CO_2), while not given enough attention as an acid-forming pollutant, has always been and will continue by far to be the most acidifying component of the biosphere. This is not only because of the effects of carbonic acid but also because of the organic acids produced in the decomposition of organic matter. The impacts of fertilization in acidification processes must also be given consideration, particularly in agriculture. Therefore, to measure the impacts of the pollutants on the environment, the effects resulting from anthropogenic emissions must be distinguished from those occurring naturally. Furthermore, all the acidifying pollutants are also essential plant nutrients and their beneficial effects must be separated from their adverse effects.

3. DIRECT EFFECTS OF SULPHUR DIOXIDE

3.1 ACUTE EFFECTS

In retrospect, problems associated with acute-type SO_2 effects to vegetation, which we were concerned about several years ago, now seem simple compared to the issues we face today. Over the past 17 years, we conducted over 350 surveys, which included about 40 000 records of ambient SO_2 concentrations and associated inspections of vegetation, for effects in the vicinities of Tennessee Valley Authority's (TVA) 12 coal-fired power plants. These data (Table 1) strongly suggest that a threshold for visible injury exists for most species. For the most sensitive crop (soybean) and forest (Virginia pine) species growing in our area, the thresholds appear to be around 831 $\mu g \cdot m^{-3}$, 1-h average, and 532 $\mu g \cdot m^{-3}$, 3-h average. The probability for occurrences of significant foliar injury, as illustrated for soybean on Table 2, is less than 4 in 100 chances, unless peak concentrations exceed 2660 $\mu g \cdot m^{-3}$. These data suggest that foliar injury can occur at SO_2 doses well below the current National Secondary Ambient Air Quality Standard (NSAAQS) of 1330 $\mu g \cdot m^{-3}$.

The data also suggest that the probability for occurrences of concentrations which may cause visible injury is very low for SO_2 sources equipped with tall stacks (>152 m) which meet the New Source Performance Standard of 1.2 lb $SO_2 \cdot 10^{-6}$ Btu (Figure 1). Thus, the principal demonstrable effect of SO_2 emissions from utilities on vegetation is rapidly being eliminated as power plants achieve compliance with emission limits defined by their respective State Implementation Plan (SIP).

We conducted some surveys during the winter in areas exposed to SO_2 levels in excess of 2660 $\mu g \cdot m^{-3}$, 1-h average, and were unable to detect visible effects on evergreens, such as loblolly, Virginia, and short-leaf pines.

3.2 CHRONIC EFFECTS

Questions remaining concerning the direct effects of SO_2 on vegetation are: Does intermittent exposure to SO_2 alone, or mixtures of SO_2 and other pollutants, at ambient concentrations less than those that cause visible injury, cause permanent economic losses? If so, how much more emission control is needed to mitigate these effects? Resolution of these issues, as we have recently pointed out (Herbert 1985), will require well-designed experiments to document the occurrences of effects under ambient conditions, or under conditions that adequately simulate ambient exposure.

Table 1. Calculated threshold concentrations for the occurrence of visible foliar SO_2 effects on 10 species, based on regression analyses.

Species	Predicted Independent Variable	95% Confidence Threshold ($\mu g \cdot m^{-3}$)	Observed Interval ($\mu g \cdot m^{-3}$)	Minimum ($\mu g \cdot m^{-3}$)	R^2
Common Evening Primrose	Ln peak	2021	1809 to 2155	1808	0.24
	Ln 1-h	931	638 to 1144	798	0.33
	Ln 3-h	585	319 to 825	559	0.39
Cranesbill	Ln peak	2181	2022 to 2261	1862	0.31
	Ln 1-h	1011	718 to 1224	958	0.39
	Ln 3-h	612	319 to 851	665	0.40
Giant Ragweed	Ln peak	2022	1889 to 2128	1862	0.19
	Ln 1-h	931	771 to 1064	798	0.27
	Ln 3-h	479	372 to 585	399	0.25
Horseweed	Ln peak	2687	a	2261	0.37
	Ln 1-h	1516	1170 to 1729	1330	0.39
	Ln 3-h	798	505 to 1047	718	0.36
Lesser Ragweed	Ln peak	1862	1756 to 1915	1702	0.20
	Ln 1-h	931	771 to 1037	771	0.22
	Ln 3-h	479	372 to 559	372	0.20
Loblolly Pine	Ln peak	2155	1915 to 2261	1955	0.29
	Ln 1-h	984	585 to 1250	931	0.30
	Ln 3-h	638	160 to 1010	692	0.28
Pennsylvania Smartweed	Ln peak	2554	2500 to 2580	2261	0.19
	Ln 1-h	931	638 to 1170	745	0.15
	Ln 3-h	479	213 to 718	399	0.12
Red Clover	Ln peak	2181	2022 to 2261	1862	0.31
	Ln 1-h	1117	213 to 1569	1330	0.17
	Ln 3-h	745	346 to 1064	718	0.29
Soybean (% Chl)	Ln peak	2155	2022 to 2234	1968	0.30
	Ln 1-h	904	665 to 1091	798	0.34
	Ln 3-h	479	293 to 638	399	0.29
Virginia Pine	Ln peak	1782	1516 to 1968	1702	0.25
	Ln 1-h	931	452 to 1250	1064	0.28
	Ln 3-h	293	0 to 798	798	0.14

[a] Rounded to two decimal places, range was zero.

Table 2. Estimated probabilities for the occurrence of >5% foliar chlorosis on soybeans by 1-h average SO_2 concentration class and peak concentration class.

1-h ($\mu g \cdot m^{-3}$)	Peak ($\mu g \cdot m^{-3}$)								
	>266	>665	>1330	>1995	>2660	>3325	>3990	>4655	>5320
266 to 665	0	0	0	0	0	0	0	-[a]	-
666 to 1330	-	0.02	0.03	0.04	0.04	0.04	0.25	-	-
1331 to 1995	-	-	0.28	0.31	0.33	0.42	0.60	1.00	1.00
1996 to 2660	-	-	-	-	0.40	0.43	0.45	0.43	0.33
2661 to 3325	-	-	-	-	-	0.67	0.60	0.60	0.75
>3325	-	-	-	-	-	-	-	-	0.73

[a] No occurrences. Blanks in the lower peak classes also indicate no occurrences since the peak concentration must be higher than the 1-h average concentration.

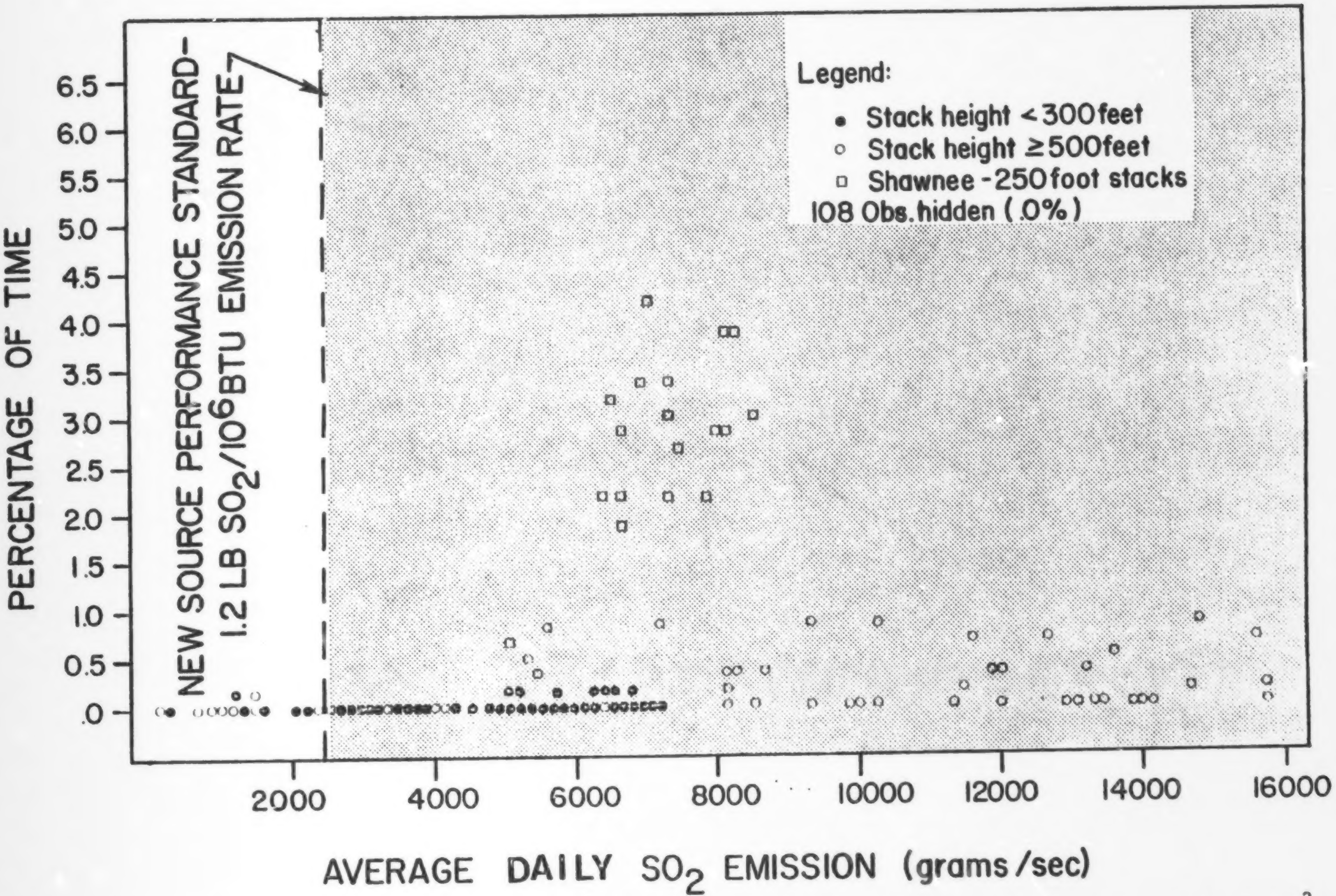

Figure 1. Relationship of percentage of time (month) that 1-h SO_2 dosages greater than 1330 $\mu g \cdot m^{-3}$ were recorded at ground level and the average daily SO_2 emission rate (grams/second), all steam plants, May through September 1974-1977.

Unfortunately, in nearly all research on the effects of chronic SO_2 exposure, these criteria have not been met. In our research:

1. The pollutant exposure regimes employed in our experiments should be representative of the range of exposure conditions experienced in the ambient environment. Therefore, we need to determine what constitutes, in terms of SO_2, ozone (O_3), and nitrogen dioxide (NO_2), exposure regimes representative of ambient conditions. Is it meaningful to measure responses based on continuous (or almost continuous) exposure to SO_2 concentrations in excess of the background of 53 $\mu g \cdot m^{-3}$, where the background is defined as the average hourly SO_2 concentration in areas far from large sources of SO_2; or on simultaneous exposure to mixtures of SO_2 and O_3; or to mixtures that contain more than 153 to 191 $\mu g \cdot m^{-3}$ of NO_2?
2. Responses should be measured in ways that can be quantified in economic terms. For example, in most cases, the effects observed following chronic exposure to low levels of SO_2 have been physiological or biochemical. Are changes in physiology and biochemistry ultimately manifested in permanent losses in growth, yield, or quality; and under what conditions relative to the rural ambient environment?
3. Dosages that elicit responses should be quantifiable in terms that will be useful in developing control strategies. How can dosage for intermittent exposures during a growing season or decades be described in terms having practical application? Is dose cumulative? Is it cumulative for all exposures or for exposures in excess of some threshold level?

3.2.1 Representative Ambient Chronic Exposure Regimes

The data in Table 3 illustrate a 5-year average growing season, daylight hours, exposure regime for a 2600-MW power plant (before it came into compliance with an allowable emission rate of 5 lb $SO_2 \cdot 10^{-6}$ Btu), and average daily emissions of about 1179 t. The exposure regime for this power plant, which has not violated ambient air quality standards, can be considered 'worst case' compared to what might be expected for power plants

Table 3. Five-year average growing season cumulative frequency distribution for hourly average SO_2 concentration, Cumberland Steam Plant, all monitors, 1977 to 1981.

SO_2 Concentration Class[a] ($\mu g \cdot m^{-3}$)	Hours SO_2 Concentration Equaled or Exceeded Class					
	A.M. 0700 to 1300		P.M. 1400 to 1700		Daylight	
	No.	Cumulative	No.	Cumulative	No.	Cumulative
266	10.0	13.0	14.0	19.0	24.0	32.0
532	2.0	3.0	3.0	5.0	5.0	8.0
798	0.0	1.0	1.0	2.0	1.0	3.0
1064	1.0	1.0	0.5[b]	1.0	1.5	2.0
1330	0.0	0.5[b]	0.5	0.5	0.5	

[a] 266 $\mu g \cdot m^{-3}$ = 160 to 399 $\mu g \cdot m^{-3}$; 532 $\mu g \cdot m^{-3}$ = 426 to 665 $\mu g \cdot m^{-3}$; etc.

[b] The same average frequency for each class.

sited in non-mountainous terrain and meeting more restrictive emission limits. Extrapolating from the data, we find the upper limits for exposure regimes that are typical for ambient conditions in the vicinity of a rural-sited power plant would consist of about 21 intermittent exposures, averaging about 1.5 h apiece, spread over a 6-mo growing season. The maximum 1-h and 3-h average SO_2 concentration would not exceed 1330 $\mu g \cdot m^{-3}$. The total hours of exposure to concentrations equal to or greater than 226 $\mu g \cdot m^{-3}$ would not exceed 32. In areas with more unstable or more windy conditions during the growing season, exposure would be less. Since these data are for all monitors, the actual exposure at any particular monitor or in any given year would be much less. Beyond 10 to 15 mi, SO_2 concentrations would rarely exceed 27 to 53 $\mu g \cdot m^{-3}$, 1-h average.

Vegetation growing within the area exposed to greater SO_2 concentrations near point sources is also exposed to other pollutants, such as O_3 and NO_2; hence, there is considerable concern about the interactive and synergistic effects of exposure to mixtures of SO_2 and other pollutants. It is important to the researcher to understand the conditions under which exposure to mixtures of pollutants can occur in the rural ambient environment, as well as the conditions that limit the dosage. In addition to SO_2 and other pollutants, one constituent of a power plant plume is nitrogen oxide (NO). The proportion of NO to SO_2 varies (depending on the boiler type) between about 1:4 and 1:8; as SO_2 emissions are reduced this ratio will increase. The NO in the plume reacts very rapidly with background O_3 to produce $NO_2 + O_2$, depleting the O_3 (McLaughlin 1981). The upper limit for production of NO_2 is determined by the background O_3 concentration and dispersion. For point sources sited in rural areas, this reaction has two practical consequences:

1. Sulphur dioxide cannot co-exist with O_3 until the reaction

$$NO + O_3 \rightarrow NO_2 + O_2$$

is complete. By the time this occurs, SO_2 concentrations have been reduced, by dispersion, deposition, and transformation, to not much more than background values. However, this may not apply in your case if NO emissions from your SO_2 sources are low or non-existent.

2. NO_2 levels cannot exceed background O_3 levels, so NO_2 will rarely exceed 115 to 153 $\mu g \cdot m^{-3}$.

Care should be exercised in the selection of controls for comparing the productivity of crops or forests exposed to pollutants with that of crops or forests not exposed to the pollutants. In measuring the effects that emissions from point sources sited in rural areas have on crop productivity, what must actually be measured is how much productivity has been reduced by the point sources emissions, beyond any reduction caused by exposure to ambient levels of pollutants from other sources. The correct control is, therefore, productivity of plants exposed to ambient levels of the other pollutants, not productivity of plants grown in air filtered to remove all pollutants. The dosages of pollutants employed in mixtures must be in the same relative proportions that would occur in ambient air when the point source plume is on the ground; i.e., for a power plant, O_3 should be depleted to less than 50 $\mu g \cdot m^{-3}$ for SO_2 dosages of more than 133 $\mu g \cdot m^{-3}$, NO dosages from 0.25 to 1.0 times the SO_2 concentration, and NO_2 dosages of less than or equal to ambient ozone concentrations.

3.3 EXPRESSION OF DOSE

Classically, dose has been expressed as concentration of a pollutant times duration of exposure in hours. For acute exposures, dose is normally expressed as a time-average concentration; e.g., 1300 $\mu g \cdot m^{-3}$ SO_2 for 3 h. This expression of dose is a useful predictor for occurrences of visible injury caused by exposure to short-term, high-concentration episodes. Because ground-level exposure near a point source results from many interacting factors--meteorology, stack height, terrain, various plant-operating variables--long-term growing seasons or annual averages in themselves usually do not adequately reflect shorter-term acute or chronic exposures that have been demonstrated to cause permanent injury. For example, annual average SO_2 concentration might not exceed 53 $\mu g \cdot m^{-3}$ in the vicinities of two power plants; but, because of the factors listed above, the emissions from one plant might cause significant effects and the emissions from the other none.

For multiple or chronic exposures, some investigators (Oshima 1975) have suggested using cumulative dose, which is calculated by multiplying the pollutant concentration by the duration of the exposure in hours and summing the individual dosages. Others (Lefoln and Benedict 1982; Heck et al. 1982) have suggested, for O_3, accumulating dosages that exceed a threshold level. Cumulative dose appears to have merit for sites that are often exposed to concentrations of O_3 high enough to cause visible injury (Heagle et al. 1973); in these cases, the vegetation was exposed nearly every day to O_3 for five or more hours. Cumulative dose has not been shown to have merit for intermittent ambient exposures to SO_2 or for exposures that simulate the ambient environment.

3.4 RESPONSE MEASUREMENTS

So far, the only measurements of plant response that are useful for decision-makers in managing air quality in the United States are those that have economic meaning for the crop in question; these include measurements of growth, yield, and quality. The secondary standards, which have been promulgated to protect human welfare, have been based largely on concentrations of a pollutant that can be demonstrated to cause permanent losses in productivity or quality. Many investigators have demonstrated physiological and biochemical responses that appear to be transient. However, the cumulative effects of these transient responses on growth, yield, or quality are not known and need to be determined.

3.5 FUTURE RESEARCH DIRECTIONS

Does intermittent exposure to ambient concentrations of SO_2 and other air pollutants cause reductions in yield? If we are to answer this question, by providing data that will be of use in managing air quality, our experimental approach to the problem must be modified. What we need to know is: How many incremental exposures to given pollutant dosages can a crop tolerate before its productivity is reduced? Research designed to answer this question should provide data that could be used to develop a statistical-type secondary standard for the number of given short-term dosages that cumulatively would reduce the productivity of crops and forests. Furthermore, the results should be useful in evaluating alternative control strategies for existing plants. Since a reduction in emissions should proportionally reduce the frequency of ground-level exposures of given concentrations, one could use frequency distributions based on historical data to calculate what reduction in emissions would be needed to avoid exceeding various dosages of a pollutant. Similarly, for new sources, models could be used to generate frequency distributions to assess the probability that damage may occur. Adequate information is available for designing experiments that would answer the question posed here and resolve the critical issues set forth earlier. We recently (Herbert 1985) suggested an experimental approach for determining the effects of chronic, low-level exposure to SO_2 on vegetation and have used it for studies with soybeans (*Glycine max* cv Essex). The objective was to determine the minimum cumulative SO_2 dose that would have to be exceeded for a reduction in yield to occur.

The SO_2 exposure treatments were based on the frequency distribution for ambient hourly average SO_2 concentrations measured over the 5-year period 1977 to 1981 near a power plant, which might be considered 'worst case' (defined as a plant meeting all NSAAQS, does not cause visible effects, and has an emission rate representative of the upper limits of SIP's). The average SO_2 concentration was calculated for each hour from 0700 to 1900 for May through October and divided into five concentration classes (Table 4). The number of ground-level exposures averaged 35 per season with an average duration of 1.5 h.

These data were used to design the treatments for experiments conducted in 1983 and 1984. A 1-h average SO_2 concentration equivalent to the mid-point of each concentration class was used to establish the level of SO_2 for each treatment. The average seasonal cumulative dose shown by the field data (1977 to 1981) was equivalent to exposures of 33 h at 266 $\mu g \cdot m^{-3}$, 8 h at 532, 4 h at 798, 3 h at 1064, and 4 h at 1330 $\mu g \cdot m^{-3}$ for a total of 52 h.

The treatments shown in Table 5 were selected for study in 1983. Treatment 2 was a slightly higher dose than the average cumulative dose in Table 4. Treatment 1 included a 3-h SO_2 exposure that exceeds the NSAAQS in an attempt to force an effect on yield. It was assumed that the higher doses would reduce yield, and the experimental approach was to systematically reduce the dose in treatments 1 through 5 until a dose was reached that did not cause a reduction in yield. Exposure to O_3 alone was used as a control (Treatment 6).

Table 4. Five-year average cumulative frequency distribution for ground-level SO_2 exposure, Colbert Steam Plant, all monitors, May through October, 1977 to 1981.

SO_2 Concentration Class ($\mu g \cdot m^{-3}$)	Total Hours SO_2 Concentration Equaled or Exceeded Class Value				
	A.M. 0700 to 1300		P.M. 1400 to 1900		Daylight
	No.	Cumulative	No.	Cumulative	(Cumulative)
266	17	28	16	24	52
532	5	11	3	8	19
798	2	6	2	5	11
1064	2	4	1	3	7
1330	2	2	2	2	4

Table 5. Exposure treatments for soybeans in greenhouse chambers during 1983 and 1984.

Treatment	SO_2 Exposure Regime 1983	SO_2 Exposure Regime 1984
1	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 6 h at 798 $\mu g \cdot m^{-3}$ + 3 h at 2660 $\mu g \cdot m^{-3}$	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 9 h at 2660 $\mu g \cdot m^{-3}$
2	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 6 h at 798 $\mu g \cdot m^{-3}$ + 3 h at 1330 $\mu g \cdot m^{-3}$	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 9 h at 1330 $\mu g \cdot m^{-3}$
3	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 6 h at 798 $\mu g \cdot m^{-3}$ + 3 h at 1064 $\mu g \cdot m^{-3}$	31 h at 266 $\mu g \cdot m^{-3}$ + 12 h at 532 $\mu g \cdot m^{-3}$ + 9 h at 798 $\mu g \cdot m^{-3}$
4	31 h at 266 $\mu g \cdot m^{-3}$ + 21 h at 532 $\mu g \cdot m^{-3}$	31 h at 266 $\mu g \cdot m^{-3}$ + 21 h at 532 $\mu g \cdot m^{-3}$
5	52 h at 266 $\mu g \cdot m^{-3}$	O_3 alone
6	O_3 alone	charcoal-filtered air

The treatments were modified in 1984 in another attempt to force effects by using even greater SO_2 doses and to include a charcoal-filtered air control treatment (Table 5).

In both 1983 and 1984, the experimental plants were fumigated for 3 h each week over a period of 17 wk, plus 1 h in the 18th week. Fumigations with hourly average SO_2 concentrations higher than 266 $\mu g \cdot m^{-3}$ were made during the pod-filling stage of growth which is generally considered the most sensitive stage for damage to soybean. During each 3-h fumigation, the SO_2 concentration was introduced as three 1-h peaks; i.e., concentration increased linearly from zero to a peak in 30 min, then decreased linearly for 30 min back to zero; this sequence was repeated two more times. With this procedure, the peak concentration was two times the hourly average concentration.

Concentration of NO_2, based on ambient monitoring data, was maintained at 114 $\mu g \cdot m^{-3}$ during SO_2 exposure. Ozone monitoring showed that concentrations during the growing season were typically between 100 and 120 $\mu g \cdot m^{-3}$ between 0800 and 1600. Therefore, plants were exposed to 120 $\mu g \cdot m^{-3}$ during these hours each weekday, except during the time of SO_2 exposure.

The only effect of SO_2 on soybeans in greenhouse chambers resulting from the 1983 treatments was a 1-wk delay in senescence by treatments 2 and 3, which had maximum 1-h average SO_2 concentrations of 1330 and 1064 $\mu g \cdot m^{-3}$, respectively (Table 6). Exposure to O_3 can cause premature senescence (Heagle et al. 1973), and these results suggest that the exposure to the intermediate levels of SO_2 reduced the impact of O_3 on the time of senescence. A filtered air treatment was included in the 1984 study to further evaluate this observation.

Soybeans developed visual foliar symptoms of O_3 and SO_2 injury during the 1984 growing season in the exposure chambers. Ozone injury appeared on soybean leaves about 4 wk after exposure began and the amount of injury increased during June and July. The percentage of the leaf area showing O_3 injury on July 30 is shown in Table 7. The results suggest that exposure to SO_2 reduced the severity of O_3 injury. Chlorosis and bronzing, typical of SO_2 injury, were observed on soybean leaves July 20, 1 wk after

Table 6. Senescence and seed yield of soybeans in greenhouse chambers, 1983.

Treatment[a]		Senescence[b]		
Number	$[SO_2]$ ($\mu g \cdot m^{-3}$)	9/12 (%)	9/19 (%)	Total Seed Weight (g)
1	2660	36a	50a	92.9
2	1330	26b	40b	91.1
3	1064	22b	38b	98.1
4	532	34a	49a	92.4
5	266	39a	53a	93.5
6	0	34a	47a	92.9

NOTE: [a] Maximum 1-h average SO_2 concentration.

[b] Means followed by the same symbol in a column are not significantly different at 0.05 level of significance.

Table 7. Foliar injury and sensescence of soybeans exposed to SO_2 and O_3 in greenhouse chambers in 1984.

Treatment[a]		Ozone	SO_2	Senescence[b]		
Number	$[SO_2]$ ($\mu g.m^{-3}$)	Injury (%)	Injury (%)	8/20 (%)	8/27 (%)	9/3 (%)
1	2660	8	36	9a	27a	35a
2	1330	9	16	8a	20b	32ab
3	1064	11	0	8a	19b	30b
4	532	18	0	4b	12c	21a
5	O_3 alone	29	0	19c	35d	50d
6	Filtered air	0	0	0d	7a	12e

[a] Maximum 1-h average SO_2 concentration

[b] Means followed by same symbol in a column are not significantly different at 0.05 level of significance.

the first 3-h exposure to 1330 $\mu g \cdot m^{-3}$. The percentage of the leaf area affected by chlorosis and bronzing is shown in Table 7.

Estimates of senescence were made at weekly intervals and the percentage of leaves showing visual signs of senescence for three dates is shown in Table 7. The results verify observations made in 1983. Soybeans exposed to O_3 alone began senescence about 2 wk earlier than soybeans exposed to charcoal-filtered air. Soybeans exposed to SO_2 and O_3 began senescence about 1 wk later than soybeans exposed to O_3 alone.

The total seed weight of soybeans exposed to O_3 was significantly less than for soybeans grown in charcoal-filtered air. This lower yield was caused by a reduction in both number and size of seed (Table 8). Using exposure to O_3 alone as the control, the only effect of SO_2 on yield was a significant increase in number of seed and total seed weight when exposed to a maximum 1-h average SO_2 concentration of 532 $\mu g \cdot m^{-3}$.

4. CONCLUSIONS

The results of this study indicate that emissions from point sources of this large size do not cause reductions in yield of soybeans, at least for the cultivar Essex. We have conducted other studies (Jones et al. 1986) with other varieties of soybeans under a wide range of ambient conditions in the field and under simulated conditions in the greenhouse. Only once (Jones et al. 1977) have we detected a significant reduction in yield of soybeans under conditions representative of the ambient environment. However, under the same conditions, we have been able to detect significant reductions, apparently caused by ozone exposure, similar to those reported by many others. Our data suggest that for the Essex cultivar, SO_2 exposure in conjunction with O_3 exposure is antagonistic to the effect of O_3 on yield. The SO_2 appears to delay O_3-caused senescence.

Table 8. Yield of soybeans in greenhouse chambers in 1984.

Treatment[a]		Total No.[b] Seed/Pot (g)	100 Seed[b] Weight (g)	Total Seed[b] Weight (g)
Number	[SO_2] ($\mu g \cdot m^{-3}$)			
1	2660	822a	11.09a	91.4a
2	1330	854ab	12.52bc	106.1ab
3	798	932abc	11.52ab	107.7b
4	532	978cd	12.64c	123.7c
5	O_3 alone	810a	11.70abc	93.3ab
6	Filtered air	1020d	13.88d	141.0d

NOTE: [a] Maximum 1-h average SO_2 concentration.
[b] Means followed by same symbol in a column are not significantly different at 0.05 level of significance.

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SOILS AND GEOLOGY SENSITIVITY MAPPING OF ALBERTA AND WESTERN CANADA

by

N. Holowaychuk,[1] R.J. Fessenden,[1] C. Palmer,[2] and J.H. Wiens[3]

ABSTRACT

Under the auspices of the Western Canada Long-Range Transport of Air Pollutants Technical Committee, maps of the four western provinces (1:2 000 000 scale), and the Yukon and Northwest Territories (1:5 000 000 scale) showing: (1) the potential of soils and geology to reduce the acidity of incoming acid deposition and (2) the sensitivity of soils to acid inputs, have been in preparation since 1983. Although these maps are being produced for each of the jurisdictions separately, the interpretive criteria were developed jointly and there has been communication and co-operation among the participants.

In Alberta, the preparation of the two interpretive maps first required that a base soils/geology map be produced. This was accomplished by assembling and synthesizing all of the soils, geological, and physiographical information for the province that was available. In all, approximately 350 map unit delineations, representing 215 distinct map unit types, were identified.

All of the map units were rated into one of three categories, high, medium, or low, for the potential of the soil and geological materials to reduce the acidity of incoming acidic deposition. The criteria were based on combinations of soil depth, exchangeable base content, bedrock type, parent material type, and soil drainage class. The intent of this base map is to portray the ability of the land to modify the acidity of precipitation and its subsequent impact on aquatic systems.

All of the map units were also rated according to the sensitivity of the soils to acid inputs. The sensitivity of three soil processes, sensitivity to base loss, sensitivity to acidification, and sensitivity to the solubilization of aluminum, were rated separately. An overall sensitivity was also assigned to each map unit. Three categories of sensitivity, high, medium, and low, were used for each of the three soil processes and the overall sensitivity.

No specific guidelines for rating Organic soils were developed by the Western Canada participants. However, because of the large areas in northern Alberta that are occupied by Organic and Organic Cryosol soils, it was felt that at least a preliminary attempt should be made to rate these soils. Accordingly, a provisional set of criteria was developed and applied. The approach taken was to recognize three peatland system

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[1] Alberta Research Council, Edmonton, AB
[2] Alberta Environment, Lethbridge, AB
[3] British Columbia Ministry of Environment, Victoria, BC

categories, Eutrophic, Mesotrophic, and Oligotrophic, that were defined on the basis of pH and base cation content of the organic matrix-ambient water system.

To conclude the co-operative and co-ordinated effort, a combined report and set of maps at a scale of 1:7 000 000 will be prepared for Western Canada. Completion and publication of maps and reports for each of the provinces and territories and for Western Canada as a whole should be accomplished by mid-1986.

ACKNOWLEDGEMENTS

A large number of individuals contributed to this project by sharing their knowledge of the soils of Alberta. Special thanks are due to Dr. W.W. Pettapiece and J.D. Lindsay in this regard. A special acknowledgment is also due to all of those current and former employees of the Alberta Research Council, Agriculture Canada, and other agencies, whose soil maps and reports constituted the major source of information for both the basic soils map and the characteristics on which the interpretive maps are based. The patient and persevering contributions of Kathy Gates, Connie Tomas, and Joan Checholik in the preparation of this manuscript are acknowledged with gratitude.

1. INTRODUCTION

In 1981, the Western Canada Long-Range Transport of Air Pollutants Technical Committee with the agreement of the Consultative Committee initiated sensitivity mapping of aquatic systems as well as soils and geology. They established co-ordinating committees for aquatic sensitivity mapping and for soil and geology sensitivity mapping. In 1982, a policy decision was made to have each western province undertake their own sensitivity mapping. The Co-ordinating Committee was to oversee development and application of criteria and methods, and to facilitate boundary correlations. The federal government undertook to map the Yukon Territory and co-operate with the Northwest Territories. Federal agencies were also to be involved in an advisory capacity. Represented on the Co-ordinating Committee were: Manitoba Environment, Alberta Environment, British Columbia Environment, Saskatchewan Institute of Pedology (for Saskatchewan Environment), Canadian Forestry Service (for Yukon), and Northern Affairs Program, Department of Indian Affairs and Northern Development (for Northwest Territories). Co-ordination between provinces and territories and compatibility of criteria and methods with work done in Eastern Canada were the basic terms of reference given by the Consultative and Technical Committees to the Co-ordinating Committee on Soils and Geology Sensitivity Mapping.

After initial identification of issues related to sensitivity mapping, the Co-ordinating Committee met in Victoria in June 1983. Background, sensitivity rating criteria, and mapping methods used in Eastern Canada were reviewed by a representative of the Lands Directorate. A decision was made at that meeting to proceed with preparation of two interpretive maps.

The first map, "Potential of Soils and Geology to Reduce Acidity of Incoming Acidic Deposition," would parallel maps prepared for Eastern Canada bearing the same title. Criteria adopted were those used in Eastern Canada with minor revisions to accommodate differences in Western Canada. The intent of this map would be to portray the ability of the land to modify acidity of precipitation and its subsequent impact on aquatic systems.

The second map to be prepared would have no parallel in Eastern Canada. It was to be entitled "Sensitivity of Soils to Acidic Inputs," and would portray the ability of soils to resist chemical changes due to acid inputs that would affect vegetation. This second map would portray the composite sensitivity rating of three soil processes believed to be particularly important to soils as a medium for plant growth. These processes, base cation loss, soil acidification, and aluminum solubilization, had been identified by a number of authors and had also been used in a preliminary way in Eastern Canada.

This paper describes in detail the approach used in Alberta to produce these maps.

2. SOILS BASE MAP

2.1 PREPARATION OF THE BASE MAP

When this project was initiated there was no soils base map available for the Province of Alberta that was suitable for interpretation for sensitivity to acid deposition or potential to reduce the acidity of atmospheric deposition. Consequently, the first task was to prepare a suitable soils base map and to assemble pertinent descriptive information that could be used for interpretation of the map units. The information for establishing the map units and for characterizing the soils was derived from published and printed sources and from file information. Soil surveys or other types of soil resource inventories that included the taxonomic classification of soils and pertinent data on their properties served as direct sources. Where such information was lacking or limited in extent, it was inferred from surficial materials, geology, physiography, and/or topography maps, and supplemented by information extrapolated from contiguous or comparable areas that had soil surveys. Figure 1 displays the regions of the province for which different categories of information were available. The specific sources of information are referenced in the following paragraphs.

Information for Region A (Figure 1) is available in the reconnaissance soil survey reports prepared by Agriculture Canada and Alberta Research Council. These reports contain information on the areal distribution of various soils as well as field descriptions and laboratory-derived data for the more important soils. Since the soils information for Region A has been entered into a computerized database (Patterson and Peterson 1984), it was possible to generate computer printout maps at a scale of 1:1 000 000 that

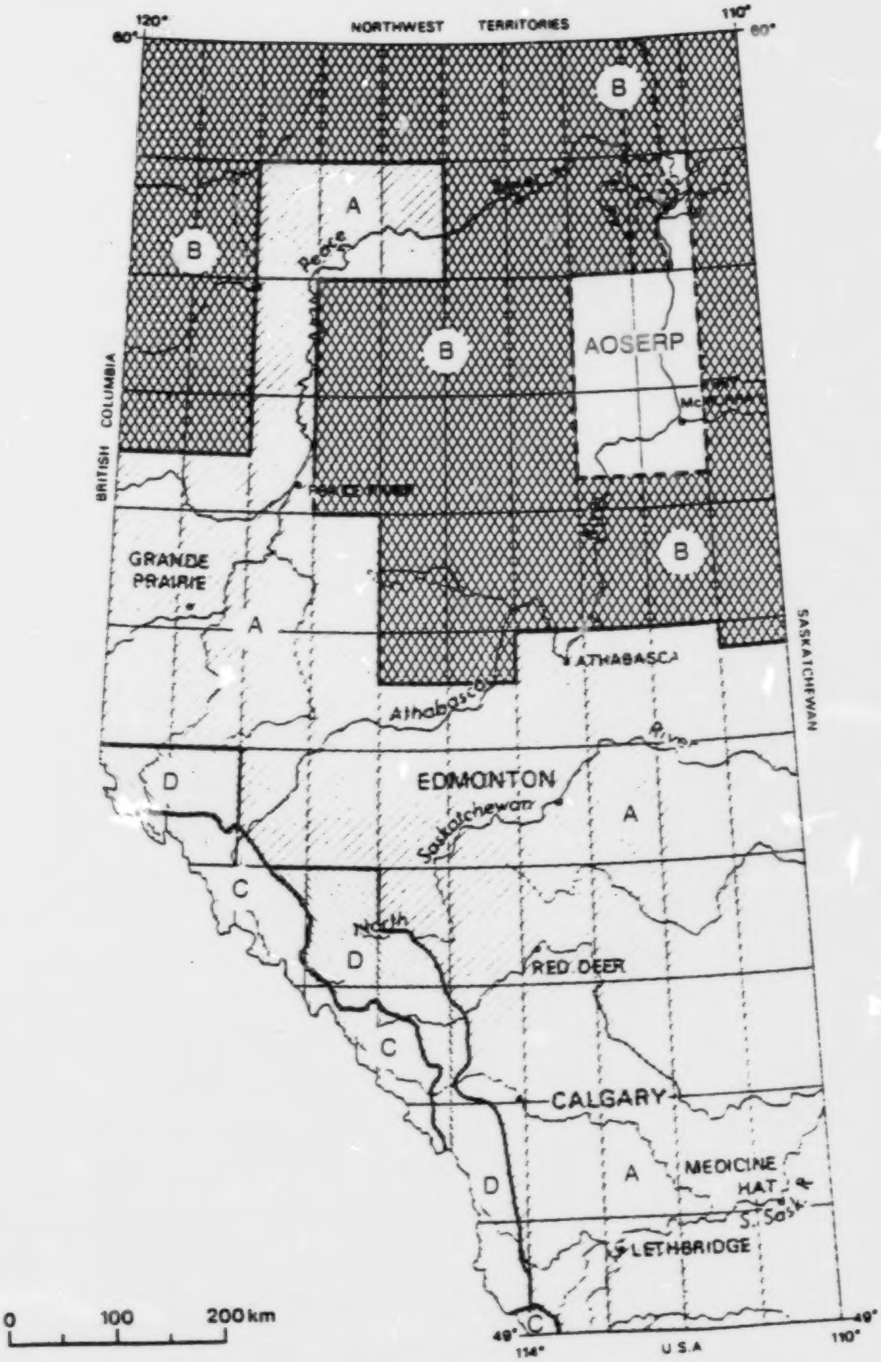
120°
60°
NORTHWEST TERRITORIES
110°
60°
B
A
Peace
B
B
AOSERP
FORT McMURRAY
BRITISH COLUMBIA
PEACE RIVER
GRANDE PRAIRIE
A
B
ATHABASCA
Athabasca
SASKATCHEWAN
D
EDMONTON
Saskatchewan
River
A
C
North
D
RED DEER
C
CALGARY
D
A
MEDICINE HAT
S. Sask.
LETHBRIDGE
C
49°
114°
U.S.A.
110°
49°
0
100
200 km

Figure 1. Soil inventory information source regions.

displayed the taxonomic class and the textural family class of the dominant soil in each quarter township. These printout maps served as the basis for establishing and delineating the map units. Concurrent examination of the soil survey maps made it possible to identify the soil series of the dominant and associated soils. This facilitated extraction, organization, and systematic compilation of the pertinent data that are usually recorded by soil series.

Information for Region B (Figure 1) is available in the exploratory soil survey reports conducted by Alberta Research Council (Lindsay et al. 1957-1964). Because of the lower intensity of survey, the map units in Region B are larger and are likely to encompass a greater variety of soils compared to the map units in Region A. The exploratory nature of the soil survey did not allow soil series to be designated. However, the information acquired was ample for at least the taxonomic classification of the more extensively distributed mineral soils and the characterization of their basic properties. Only general information was available in these reports for Organic soils. Detailed soils information similar to that for Region A was available for the Alberta Oil Sands Environmental Research Program (AOSERP) (Figure 1) area (Turchenek and Lindsay 1982).

The soils information in Region C was derived from the Ecological (Biophysical) Land Classification of Banff and Jasper National Parks (Holland and Coen 1982) and the Soil Survey of Waterton Lake National Park (Coen and Holland 1976). Since both of these surveys involved large-scale mapping and acquisition of considerable data on the properties of the soils, they provided good information on the definition, delineation, and characterization of the map units.

Region D (Figure 1) includes parts of the Rocky Mountains outside of the national parks and also the southern and south-central portions of the foothills as outlined by Pettapiece (Physiographic Map of Alberta, Agriculture Canada, 1984). The definition and delineation of the map units in the region north of Jasper Park were based on information derived from Alberta Energy and Natural Resources (AENR) Physical Land Classification maps, a report by Ferguson (1980), the surficial materials map by Bayrock and Reimchen (1974-1975), and the geology map by Green (1970). The characterization of the map units is based largely on extrapolation of information reported by Holland and Coen (1982) for Jasper Park and Twardy and Corns (1980) for the Wapiti map sheet. Similar sources of information on surficial materials and geology and the extrapolated information from Holland and Coen (1982) were employed for the area south of Banff National Park. A study by Jeffrey et al. (1968) provided additional information for a small portion of the southern Rocky Mountains area.

Comparable sources of information were employed for defining, delineating, and characterizing the map units in the foothills portion of Region D. The AENR Physical Land Classification maps and reports by Karpuk and Levinsohn (1980), Kocaoglu (1983), Kocaoglu and Sauchyn (1980), Tedder (1980), and the Alberta Institute of Pedology report by Pettapiece (1971) were all consulted. The data reported in the Hinton-Edson soil survey report (Dumanski et al. 1972) served as an important source of information for extrapolation. An ongoing soil survey in the Cardston area (Brierley, personal communication, 1985) was a source in the extreme southern part of the foothills. In addition, soil surveys conducted by one of the authors (N. Holowaychuk) in three small areas about 10 km^2 each in the central and southern foothills provided information on the classification of the soils and data regarding their properties in the areas surveyed. Surficial materials (Bayrock and Reimchen 1974-1975) and bedrock geology maps (Green 1970) were also used as supplemental information for inferring the distribution and the properties of the soils. It is recognized that in Region D, because of the varied and largely general and, in places, inferred or extrapolated information, the classification of the soils and the delineation and characterization of the map units are likely to be tenuous in some places.

2.2 CHARACTERIZATION OF THE MAP UNITS

The soils map depicts the areal distribution of the various kinds of soils occurring in the province. Each map unit encompasses areas in which a certain kind of soil is dominant. Usually, however, other kinds of soils are included in the map unit delineations, some constituting more than 20% of the area. In such cases, the most extensive of the latter soils is considered to be a subdominant component of the map unit. Some of the other kinds of soils, although of minor extent, may contribute appreciably to the qualities of the map unit delineations. The characteristics of the dominant and the subdominant soils that served as the bases for establishing the map units include taxonomic class (Canadian System of Soil Classification 1978), reaction (pH), and, for mineral soils, the texture and the kind and quality of the parent material or the substrate on which the soils occur.

3. SOIL SENSITIVITY TO ACID INPUTS

3.1 SENSITIVITY CRITERIA FOR MINERAL SOILS

The criteria for rating the sensitivity of mineral soils to acid deposition are presented in Table 1. The table is based on the recognition of 16 categories defined on the basis of cation exchange capacity and pH. For each of these categories, the sensitivity of three soil processes, sensitivity to base loss, sensitivity to acidification, and sensitivity to the solubilization of toxic elements such as aluminum, are rated separately. These are combined in the last column into an overall sensitivity rating. The sensitivity rating is based on an interpretation of the characteristics and properties of the surface layer of soil (approximately 20 cm thick).

3.1.1. Sensitivity to Base Loss

Base loss refers to the loss of basic cations, primarily Ca^{2+}, Mg^{2+}, and K^+, from the surface layers of the soil. This base loss is caused by the displacement of these basic cations by acidic cations such as H^+ and the leaching of these displaced basic cations by water moving through the profile. The displacing efficiency of H^+ is greatest in soils of high pH and percent base saturation and decreases as pH and base saturation decreases (Wiklander 1980).

Base saturation refers to the percentage of the total cation content of a soil that comprises basic cations (Brady 1984). Percent base saturation is not addressed specifically in Table 1; however, there is a good general relationship between percent base saturation and pH, although the specific relationship does differ between different kinds of soil (Mehlich 1942). In general, base saturation is about 80% or greater in soils with pH values greater than 6.0 in the surface layers of mineral soils in Alberta. In strongly acid soils (pH <5.6) and extremely acid soils (pH <4.6), the base saturation decreases more or less gradually from about 70% to about 10%.

Table 1. Criteria for rating the sensitivity of mineral soils to acid inputs.

CEC (cmol(+)kg^{-1})	pH	Sensitivity to: Base Loss	Acidification	Al Solubilization	Overall Sensitivity
<6	to <4.6	H	L	H	H
	4.6 to 5.0	H	L	H	H
	5.1 to 5.5	H	M	H	H
	5.6 to 6.0	H	H	M	H
	6.1 to 6.5	H	H	L	H
	>6.5	L	L	L	L
6 to 15	<4.6	H	L	H	H
	4.6 to 5.0	M	L	H	M
	5.1 to 5.5	M	L to M	M	M
	5.6 to 6.0	M	L to M	L to M	M
	>6.0	L	L	L	L
>15	<4.6	H	L	H	H
	4.6 to 5.0	M	L	H	M
	5.1 to 5.5	M	L	M	M
	5.6 to 6.0	L	L to M	L to M	L
	>6.0	L	L	L	L

Note: CEC = Cation Exchange Capacity
H = High
L = Low
M = Medium

In soils with pH values above 5.5, and especially above 6.0, the base saturation is high, but the conditions are conducive to appreciable loss of bases due to the high efficiency of H^+ to replace exchangeable bases (Wiklander 1980) and the inherent prevalence of bicarbonate anions that facilitate their leaching (Gasser 1973). Below pH 5.5, there is a reduction in the efficiency of acid cations to release exchangeable bases and, with the inherent lower base saturation, some mobilization of bases still occurs, but at a decreased rate. Leaching of the mobilized bases in these acid conditions is facilitated largely by sulphate and nitrate anions (Abrahamsen 1984). These ions are most often associated with acid deposition.

Sensitivity to base loss has been interpreted in at least two different ways. The first approach has been to equate high absolute base loss with high sensitivity and low absolute base loss with low sensitivity. The second approach (Cowell et al. 1981) has been to focus on relative base loss, that is, absolute base loss at a proportion of the total base reserve. In this second approach, a high relative base loss is equated with high sensitivity and a low relative base loss with low sensitivity. These two approaches lead to dramatically different sensitivity interpretations. Using the first approach, soils of high percent base saturation (pH >6.0) are considered to be highly sensitive to base loss because they experience high absolute base loss when subjected to a given amount of acid deposition, whereas soils of low percent base saturation are considered to be of low sensitivity because the absolute base loss is lower given the same amount of acid deposition. Using the second approach, soils of low percent base saturation (low pH) are considered to be highly sensitive because, while the absolute base loss is low, the relative base loss is high (Mollitor and Raynal 1982). Soils of high percent base saturation are considered to be of low sensitivity because, while the absolute base loss is high, the relative base loss is low. The latter approach has been adopted in the development of Table 1. The rationale for this is that relative base loss is more important than absolute base loss in terms of the potential effect of acid deposition on the availability of Ca, Mg, and K to plants, and hence on plant productivity (or soil fertility).

Cation exchange capacity has a modifying influence on the interpretation of sensitivity to base loss. Cation exchange capacity taken together with pH provides a basis for estimating the total base reserves in a soil (Wang and Coote 1981). In soils with a low cation exchange capacity, the total base reserves will be relatively small even though base saturation may be quite high. Consequently, all soils of low cation exchange capacity (<6.0 cmol(+)kg^{-1}) and pH <6.5 are rated as highly sensitive to base loss. For any given percent base saturation, the total base reserve increases as cation exchange capacity increases, as is shown in Table 1.

3.1.2 Sensitivity to Acidification

Sensitivity to acidification is an estimate of the change (decrease) in pH that a soil would likely experience relative to a given addition of acidity. It is inversely related to buffering capacity. Bache (1980) defines buffering capacity as the amount of acid or base required to change the pH of the soil by one unit. Soils with a low buffering capacity have a high sensitivity to acidification; conversely, soils with a high buffering capacity have a low sensitivity to acidification.

Bache (1980) considers cation exchange capacity as the main factor that determines the buffering capacity of soils. Cation exchange capacity is directly related to the mineral (clay) and organic (organic matter) colloid content of the soil. Therefore, soils that are high in clay and/or organic matter will tend to have a high cation exchange capacity, a high buffering capacity, and a low sensitivity to acidification. Conversely, soils that are low in clay and/or organic matter (for example, sands and loamy sands) tend to have a low cation exchange capacity, a low buffering capacity, and a high sensitivity to acidification.

The nature and magnitude of the buffering system in soil varies with soil pH (Thomas and Hargrove 1984). Generally, soils that have a pH of 6.5 or greater tend to be well buffered by a carbonate-bicarbonate buffering system. Acid soils, or soils with a pH of 3.5 to 5.5, also tend to be well buffered; however, in this case the hydrolysis reactions of aluminum provide the main buffering system. All other things being equal, soils in the pH range of 5.0 to 6.5 tend to be less well buffered than more acid or alkaline soils as was illustrated by Holowaychuk and Lindsay (1982). In this pH range, aluminol groups on the clay minerals, and some functional groups on organic colloids, provide some buffering capacity, but are not as effective as either the aluminum or carbonate based buffer systems.

The criteria for assessing sensitivity to acidification in Table 1 reflect the above discussion. The soils that are most sensitive to acidification are those soils with low cation exchange capacity in the pH range of 5.5 to 6.5. All soils with a pH of greater than 6.5 or less than 5.0 have low sensitivity to acidification. Soils with moderate to high cation exchange capacity and with a pH of 5.5 to 6.0 have medium to low sensitivity.

Alberta soils, especially those derived from continental glacial deposits (Pawluk and Bayrock 1969), are young in a geological sense, and therefore they have a relatively high content of weatherable soil minerals. Mineral weathering acts to counteract acidification (Bache 1983). This factor has also been taken into consideration in the assignment of sensitivity ratings to acidification and base loss.

3.1.3 Sensitivity to Solubilization of Aluminum

The solubilization of toxic elements, especially aluminum, is one of the soil chemical processes that is considered in estimating soil sensitivity. The rate of solubilization that is considered to be insignificant in neutral and slightly acid soils shows a minimal increase at about pH 6.0 and increases gradually to about pH 5.5. Sufficient aluminum is solubilized in this pH range to be toxic to sensitive plant species (Hoyt et al. 1974; Penney et al. 1977), but at and below this pH range, the rate of solubilization assumes a progressively more marked increase (Abrahamsen 1984; McKenzie and Nyborg 1984). Even the more tolerant species are affected in the pH 5.5 to 5.0 range, and it is postulated that some mobilized aluminum may appear in the soil solution effluent. Considerably more solubilized aluminum is likely to be generated in soils of pH 5.0 or lower (Abrahamsen 1984), so that effluent waters from such soils may contain sufficient solubilized aluminum to be deleterious to aquatic ecosystems. The estimated sensitivity categories of this soil chemical process are presented in Table 1.

3.1.4 Overall Sensitivity

The ratings for the sensitivity of the three soil processes were combined into an overall sensitivity rating (Table 1). In all cases, if two or more of the processes were rated as highly sensitive, the overall sensitivity rating was high. In cases where only one of the processes was rated as high and the others as moderate or low, or where none of the processes was rated as high but two or more of the processes as medium, the overall sensitivity was medium. Where all of the processes were rated as low or low to medium, an overall rating of low was assigned.

Soils that were assigned an overall sensitivity rating of high were those soils with a pH of 4.6 or lower and low cation exchange capacity soils with a pH of 6.5 or lower. Soils that were assigned an overall sensitivity rating of medium are those soils with a cation exchange capacity of greater than 6 cmol(+)kg^{-1} and a pH range of 4.6 to 5.5, and soils with a pH range of 5.6 to 6.0 and cation exchange capacity between 6 and 15 cmol(+)kg^{-1}. All other soils were given a low rating.

3.1.5 Sensitivity of Mineral Nonsoil Components

A number of map units include components that consist of rock or rock materials that may have some very shallow soils, or of surficial, largely non-rocky mineral materials on which soils had not developed or the soils are thin and very variable. These materials are referred to as nonsoil components of some map units and consist of five types of rock and four types of surficial materials (defined in Table 5, Section 4). The sensitivity rating of the nonsoil components is based on the inferred general buffering properties of the materials as indicated in Table 5.

3.2 ORGANIC AND ORGANIC CRYOSOL SOILS

3.2.1 General Description

Organic soils and their counterparts with permafrost, the Organic Cryosol soils, are derived from the accumulation of detritus from vegetation (moss, sedges, grasses, trees, or shrubs) common to poorly drained habitats. The depth of these accumulations may range from less than a metre to several metres. There are some vertical differences in the characteristics of these soils. As Ingram (1978) indicates, the upper or surface layer, which may be up to about 50 cm deep, contains an oscillating water table, is more porous, has high hydraulic conductivity, is subject to periodic or intermittent aeration, and is the zone of appreciable proliferation of plant roots. Below this upper layer, the soil is more consistently waterlogged and anaerobic, and has lower hydraulic conductivity. These soils in Alberta also vary in the depth to the mineral substrate materials that are often present within a metre of the surface. Considered on a volume instead of weight basis, these soils in the undrained state are about 10% organic matter and 90% ambient water and probably should be thought of as organic matrix-ambient water systems. Because of their constitution and hydrology, these soils as terrain components are transitional between terrestrial and aquatic ecosystems. Their ambient water is of atmospheric origin to varying degrees, but a considerable proportion of these soils receives additional water from runoff or as groundwater influx. Because of the different sources of the waters, the additions of dissolved mineral constituents into the system differ widely in quality and quantity.

3.2.2 Sensitivity of Organic and Organic Cryosol Soils to Acid Inputs

3.2.2.1 Peatland systems in Alberta. Considerable attention has been directed to the recognition and assessment of the effects of acid deposition on terrestrial and aquatic ecosystems. In contrast, as Gorham et al. (1984) have emphasized, very little research has been done regarding the sensitivity of peatlands. Because of this lack of information, no specific guidelines for defining criteria were adopted by the Western Canada participants. However, since large areas of the northern half of Alberta are occupied by Organic and Organic Cryosol soils, it was felt that at least a preliminary attempt should be made to evaluate their sensitivity to acid deposition. The approach taken was to group these soils into three categories of peatland systems based upon a synthesis of the limited chemical data that were available. These three categories and the ranges in values for some pertinent properties of the organic matrix and ambient water are presented in Table 2. The data for this table were derived from Horton et al. (1979), Karlin and Bliss (1984), Moore (1985), Slack et al. (1980), Turchenek et al. (1984),

Table 2. Some properties of Alberta peatland systems.

		Organic Matrix					Surface (Pool) Water	
Peatland System	Layer	Depth (cm)	pH	Cation Exchange Capacity (cmol(+) L^{-1})	Exchangeable Bases (cmol(+) L^{-1})	% Base Saturation	pH	Ca^{2+} + Mg^{2+} (cmol(+) L^{-1})
Eutrophic	surface	0 to 40	6.0 to 8.0	9 to 12	8 to 10	70 to 100	6.5 to 8.0	2 to 5
	subsurface	40 to 120	6.0 to 7.5	15 to 20	10 to 18	65 to 100		
	below subsurface	>120	6.0 to 7.5	15 to 20	10 to 18	65 to 100		
Mesotrophic	surface	0 to 40	4.5 to 6.0	9 to 12	2 to 8	25 to 70	5.0 to 6.5	0.5 to 2
	subsurface	40 to 120	5.0 to 6.5	15 to 20	4 to 12	30 to 70		
	below subsurface	>120	5.5 to 6.5	15 to 20	6 to 15	40 to 75		
Oligotrophic - Organic soils	surface	0 to 40	3.5 to 5.5	9 to 12	Tr[a] to 2	10 to 25	3.5 to 5.5	>0.5
	subsurface	40 to 120	3.5 to 5.5	15 to 20	2 to 6	15 to 40		
	below subsurface	>120	4.5 to 6.0	15 to 20	4 to 12	25 to 70		
Oligotrophic - Organic Cryosol soils	surface	0 to 40	3.5 to 5.5	9 to 15	Tr to 6	5 to 50	3.5 to 5.0	<0.5
	subsurface	40 to 80	3.5 to 5.5	10 to 15	Tr to 7	5 to 60		
	below subsurface	>80 (perm. frozen)	4.5 to 6.0	10 to 15	2 to 12	15 to 90		

Note: The following bulk density values used for the weight-volume conversions are based on data reported by Turchenek and Lindsay (1982) and Turchenek et al. (1984):

0.07 $mg \cdot m^{-3}$ - surface layer in all systems and all layers of Organic Cryosol soils
0.12 $mg \cdot m^{-3}$ - below surface and below subsurface layers of all Organic soils

[a] Tr = Trace

Turchenek and Lindsay (1982), Vitt et al. (1975), Walmsley and Lavkulich (1973), and a number of soil survey reports for west-central, east-central, and the Peace River regions of Alberta. These categories are based on the chemical properties of the Organic and Organic Cryosol soils and their associated pool waters and are designated as peatland systems with emphasis that they be considered as organic matrix-ambient water systems. The data for the pool water are assumed to be indicative of the chemical properties of the ambient water. As evident in the table, there is some overlap in the pH and base cation data that had been reported for the Mesotrophic and Oligotrophic peatland systems. These peatland system designations were adapted from Jeglum (1973) and Stanek and Worley (1983). Almost all of the Oligotrophic peatland systems shown on the maps consist of Organic Cryosol soils.

3.2.2.2 Sensitivity of Alberta peatland systems to acid inputs. A proposed scheme for rating the sensitivity of Alberta peatland systems is presented in Table 3. The sensitivity rating for each of the three soil chemical processes is based on the base cation content and pH of the ambient water and the pH, cation exchange capacity, and base saturation of the organic matrix. The position relationship among the base cation content, pH, and alkalinity of Alberta peatland waters, shown by Turchenek et al. (1984), and the relationship between pH, alkalinity, and buffering properties of bog and fen waters, reported by Gorham et al. (1984), served in part as the rationale for the criteria that were adopted. It was considered that the pH and base cation content of the ambient water, and hence its buffering qualities, are a reflection of the chemical properties of the organic matrix-ambient water system. It was also considered that the capacity of the system to sustain these buffering qualities is dependent on the pH, cation exchange capacity, and base saturation of the organic matrix and on the possibility of additions of bases by minerotrophic waters. These assumptions and the data given in Table 2 constituted the basis for the criteria employed in rating the sensitivity of the peatland systems as discussed subsequently. It should be stressed that this scheme and the criteria are based on meager data and some assumptions, and should, therefore, be considered to be provisional.

Table 3. Sensitivity of Alberta peatland systems to acid inputs.

Peatland System	Sensitivity to: Base Loss	Acidification	Al Solubilization	Overall Sensitivity
Eutrophic	L	L	L	L
Mesotrophic	H	H	M	H
Oligotrophic	L	L	H	L

NOTE: L = Low
M = Medium
H = High

3.2.2.2.1 Sensitivity of Eutrophic systems. It is inferred from the data in Table 2 that the relatively high base cation content of the pool water and the high base saturation of the organic matrix are indicative of the capacity of the system to sustain a high level of bicarbonate buffering, and that acidification and relative base loss will be minimal. Because of the high pH, aluminum solubilization will likewise be negligible. It is also postulated that the base cation concentration of the water will not decrease significantly due to equilibration with the considerable base reserve as indicated by the high base saturation in the organic matrix, and the influx of base-charged minerotrophic waters from soil surface runoff and groundwater sources. Thus, the sensitivity of all processes is rated as low, as is the overall sensitivity.

3.2.2.2.2 Sensitivity of Mesotrophic systems. The base cation content of the ambient water in this system ranges from moderately low to moderately high, and the pH from about 5.0 to about 6.5. Base saturation of the organic matrix surface layer ranges from very low to medium. The base content of the ambient water is indicative of moderately high to low bicarbonate content, hence moderately high to low buffering capacity. An addition of strong acidity will rapidly deplete the buffering in the low range of alkalinity and, with further additions, progressively reduce the buffering capacity remaining, but with only minimal change in pH where some of the original bicarbonate buffering remains (Gorham et al. 1984). Under these conditions, the base loss would be high and acidification moderate. In situations where the original bicarbonate content is below the moderately high level, both acidification and base loss rates would be high, and aluminum solubilization medium to high. This condition is considered to be the more common in most of the Mesotrophic peatland systems in Alberta. Some replenishment of the base cations can be expected by influx of minerotrophic water and a modest amount from the exchange base reserve of the organic matrix but the capacity of this peatland system to sustain carbonate buffering is considered to be low to moderate. The Mesotrophic systems in Alberta are rated as highly sensitive to base loss and acidification and their sensitivity to aluminum solubilization is rated as medium. Overall, the sensitivity of Mesotrophic systems to acid deposition is considered to be high.

3.2.2.2.3 Sensitivity of Oligotrophic systems. These systems are extremely to very strongly or strongly acid with very meagre contents of base cations in the ambient water as indicated in the data in Table 2. The base saturation of the organic matrix is very low to low in the surface layer. The very low base cation content of the ambient water indicates that there is very little or no bicarbonate buffering. Rather, these systems are buffered in the extremely to very strongly acid range by aluminum and humic acid systems as discussed by Johannesen (1980). Additions of acid will cause little if any change in pH. Clymo (1984) estimates that what bases may be present in the acid deposition will exchange for H^+ of the organic acids derived from the growth of sphagnum moss to increase total acidity. Braekke (1981) also indicates that base cations are strongly fixed by humic acids. Data indicating retention of calcium in the surface layer of ombrotrophic (oligotrophic) peat as reported by Damman (1978) support these other observations. These conclusions led to the assumption in this report that sensitivity to base loss is also low in these systems. Sensitivity to aluminum solubilization will be high due to the extremely acid condition if sources of aluminum such as mineral dust or associated mineral soil or rock materials are available. The overall sensitivity to acid deposition is considered to be low.

3.2.2.3 Peatland map units. A total of 30 map units in which Organic or Organic Cryosol soils are the dominant components were established. Of these, 5 are designated Oligotrophic, 23 Mesotrophic, and 2 Eutrophic. This relatively large number of map units was delineated to facilitate the identification of the different kinds of associated mineral substrate materials and the kind of associated subdominant mineral soils. With additional and more extensive investigation, these latter components could possibly serve as clues to the general water chemistry of the contiguous peatland systems. The influence of the mineral substrate may be of appreciable significance in this regard where the peat is shallow (<120 cm), a condition of variable extent and occurrence in the map units. All of the map units were established on the basis of information obtained by reconnaissance (Region A, Figure 1) or exploratory (Region B, Figure 1) soil surveys. The information obtained on kind and distribution of soils in Region B is very general, and especially with regard to peatland systems. Those map units in Region B that show Mesotrophic peatland systems as the dominant components are likely to include appreciable and varying proportions of Oligotrophic and Eutrophic peatland systems as well. For almost all of these map units, only very general descriptions of the peatland systems were available. For the majority of map units there were no available data on the chemical properties. The peatland system designations assigned to these map units were premised on this general information supplemented by that available in the few localized areas where intensive investigations had been conducted. Because of the paucity of soil survey information and the assumptions that had to be made, the map unit designations and the subsequent interpretations should be considered provisional. There is a need for more detailed soil survey information and for research into the impacts of acid deposition on peatland systems in Alberta.

3.3 DISTRIBUTION OF SOILS IN ALBERTA RELATIVE TO THEIR SENSITIVITY TO ACID INPUTS

The distribution of soils in Alberta relative to their sensitivity to acid inputs is illustrated in Table 4. Expressed as a percentage of the total area of the province, soils of high sensitivity occupy 22.7%, soils of medium sensitivity occupy 30.6%, and soils of low sensitivity occupy 44.4%. The remainder of the area of the province is occupied primarily by waterbodies.

The major groups of soils comprising the high sensitivity category are the Mesotrophic Peatlands located in the northern and northeastern portions of the province; the Dystric Brunisols located in the northeastern portion of the province; and the areas of non-carbonate rocks in the mountains and granite type rocks in the Precambrian Shield area. The remaining areas of highly sensitive soils are scattered throughout the province and are mainly composed of the coarser textured members of the Chernozemic, Luvisolic, and Brunisolic orders. As discussed in Section 3.2.2.3, both the area estimate and the rating for the Mesotrophic peatland system included some assumptions and must be considered tentative. However, both the area estimate and the rating for the Dystric Brunisol soils are based upon more certain information. An additional cause of concern for

Table 4. Distribution of soils in Alberta relative to their sensitivity to acid deposition.

Soil	Area (% of province)			
	High Sensitivity	Medium Sensitivity	Low Sensitivity	Total
Brown Chernozem	0.8	-	4.3	5.1
Dark Brown Chernozem	0.8	-	5.3	6.2
Black Chernozem	-	-	9.1	9.1
Dark Gray Chernozem	-	-	1.0	1.0
Dark Gray Luvisol	-	-	1.4	1.4
Orthic Gray Luvisol	1.0	18.9	0.1	19.9
Brunisolic Gray Luvisol	0.3	5.0	0.1	5.3
Podzolic Gray Luvisol				
Solonetzic Gray Luvisol	-	2.9	1.2	4.1
Solonetz	-	2.1	2.9	4.9
Solod	-	-	1.6	1.6
Dystric Brunisol	3.1	1.0	-	4.1
Eutric Brunisol	1.1	0.3	3.0	4.4
Organic	13.4	-	2.3	15.7
Organic Cryosol	-	-	6.6	6.6
Podzol	0.1	-	-	0.1
Rock, Rough Broken Land	2.0	0.2	1.6	3.8
Gleysol	0.1	0.2	2.8	3.1
Regosol	-	-	1.1	1.1
Total	22.7	30.6	44.4	97.5[a]

[a] Waterbodies account for about 2.5% of the provincial area.

these soils is that they occur extensively in an area where oil sands development is taking place.

The major groups of soils placed in the medium sensitivity category are the Orthic Gray Luvisols and the Brunisolic and Podzolic Gray Luvisols. These soils have very extensive distribution in the central and eastern slopes regions of the province and, taken together, comprise almost one-quarter of the total area of the province. There are also large areas of Solonetz and Solonetzic Gray Luvisol soils that are classed as being of medium sensitivity.

Soils of the Chernozemic Order, the most productive agricultural soils in the southern and central regions of the province, and the Black and Dark Gray Solod soils in the Peace River area are primarily rated as being of low sensitivity. The Oligotrophic and Eutrophic Peatland Systems are also placed in this category of low sensitivity.

4. POTENTIAL OF SOILS AND GEOLOGICAL MATERIALS TO REDUCE THE ACIDITY OF ACID DEPOSITION

All of the dominant and subdominant soil and nonsoil components of the map units were rated with regard to their potential to reduce the acidity of incoming acid deposition. The criteria that were used in Alberta are presented in Table 5. For mineral soils and geological materials, the criteria are based on guidelines and criteria that were developed for Eastern Canada (Working Group 1, 1983), and that were adopted by Western Canada participants (Weins 1983). In Alberta, additional criteria were developed to rate map units dominated by Organic and Organic Cryosol soils.

4.1 CRITERIA FOR MINERAL SOILS AND GEOLOGICAL MATERIALS

The rating of the potential of mineral soil components was based on combinations of soil depth, exchangeable base content, type of substrate bedrock or parent material, and soil drainage class as shown in Table 5. The poorly drained soils, represented by Gleysol soils in the map units, were rated as having a high potential. For nonsoil (geological materials) map unit components, the inferred buffering properties of the types of rock or surficial materials, as defined by Table 5, served as the basis for the ratings. Carbonate rocks or calcareous surficial materials were given a high

Table 5. Criteria for potential of soils and geology to reduce acidity of incoming acid deposition.

Potential	Depth (cm)	Exchangeable Bases (cmol(+) kg^{-1})	Bedrock Type[a]	Surficial Parent Material Type[b]
High	<25	all ranges	I,V	A
	25 to 100	>15	I, II, V	A, B
	25 to 100	6 to 15	I, V	A
	25 to 100	<6	I, V	A
	>100	>15	all types	all types
	>100	6 to 15	I, V	A
	poorly drained soils	all ranges	all types	all types
	Eutrophic Peatlands	-	-	-
Medium	<25	all ranges	II, III	-
	25 to 100	6 to 15	II, III	B, C
	25 to 100	<6	II, III	B
	>100	6 to 15	II, III, IV	B, C, D
	>100	<6	I, V	A
	Mesotrophic Peatlands	-	-	-
Low	<25	all ranges	IV	-
	25 to 100	<6	IV	C, D
	>100	<6	II, III, IV	C, D
	Oligotrophic Peatlands	-	-	-

[a] Bedrock Types:

I = Carbonate rock (limestone, dolomite) or calcareous clastic sedimentary rocks: shales, siltstone, sandstone. High buffering capacity.

II = Intermingled carbonate rocks (limestone, dolomite) and clastic sedimentary rocks that are more commonly fine or medium grained: shale, siltstone, some sandstone. Some of the clastic sedimentary rocks are slightly acid to mildly alkaline in reaction and may include sporadic calcaresous strata. Moderately high buffering capacity.

III = Clastic sedimentary rocks: shale, siltstone, sandstone. More commonly fine or medium grained. In frequent calcareous strata. Medium buffering capacity.

IV = Granite and granite type rocks. Low buffering capacity.

V = Largely alkaline clastic sedimentary rocks; some of which may be saline to some extent: shale, siltstone, sandstone. High buffering capacity.

[b] Surficial or Parent Material Types:

A = Calcareous or mildly alkaline and saline materials. All texture classes. High buffering properties.

B = Noncarbonate bearing clayey or sporadically weakly calcareous clayey and fine loamy materials. Moderately high buffering properties.

C = Largely noncarbonate bearing but in places may be very sporadically weakly calcareous fine loamy materials. Moderate buffering properties.

D = Noncarbonate bearing coarse loamy, sandy, and sandy skeletal class materials. Low buffering properties.

rating, while granite-type rocks were rated as having a low potential. Also, clayey or fine loamy materials were considered to be more effective in reducing the acidity of atmospheric deposition than sandy materials.

4.2 POTENTIAL OF ORGANIC AND ORGANIC CRYOSOL SOILS TO REDUCE THE ACIDITY OF ACID DEPOSITION

The Organic and Organic Cryosol soils are considered as peatland systems: Eutrophic, Mesotrophic, and Oligotrophic, as defined previously in Section 3.2.2.1. The chemical properties of the peatland systems, based on the chemical qualities of the organic matrix and the ambient water, are indicated by the data presented in Table 2. Eutrophic peatland systems have a high pH and a relatively high concentration of base cations reflecting a sustained influx of base-charged minerotrophic waters. The acidity neutralizing potential of this system is postulated to be high. Mesotrophic systems are of intermediate reaction (pH) and base cation concentration in the surface layer, but become less acidic with depth. It is expected that incident acidity will acidify the surface layer water, but that the discharge effluent will be moderated to a varying degree by influx from the lower layers to contribute to a medium potential to reduce the acidity. The surface layer water of Oligotrophic systems is extremely to strongly acid, and little if any moderating influence from the lower layers is likely to occur, especially in Organic Cryosol soils in which these layers are perennially frozen (Lindsay and Odynsky 1965; Turchenek and Lindsay 1982). A low potential to reduce acidity is predicted for these systems.

4.3 POTENTIAL OF SOILS AND GEOLOGICAL MATERIALS IN ALBERTA TO REDUCE THE ACIDITY OF ACID DEPOSITION

The areal extent of the three categories of the potential of soils and subsurface geological materials to reduce the acidity of atmospheric deposition is presented in Table 6. Approximately two-thirds (64.4%) of the total area of the province is occupied by soils and geological materials rated as having a high potential to reduce the acidity of atmospheric deposition. A further 21.8% of the area of the province is rated as having a medium potential, and only 11.3% is rated as having a low potential.

Table 6. Potential of soils and geology in Alberta to reduce acidity of incoming acid deposition.

Soils	Area (% of Province)			
	Low Potential	Medium Potential	High Potential	Total
Chernozem	-	1.6	19.8	21.4
Luvisol	0.3	3.1	27.3	30.7
Solonetz	-	-	4.9	4.9
Solod	-	-	1.6	1.6
Brunisol Podzol	3.3	2.1	3.2	8.6
Organic Organic-Cryosol	6.6	13.4	2.3	22.3
Non-soil	1.1	1.6	1.1	3.8
Gleysol	-	-	3.1	3.1
Regosol	-	-	1.1	1.1
Total	11.3	21.8	64.4	97.5[a]

[a] Waterbodies account for about 2.5% of the provincial area.

A very large portion of the Plains Region with the exception of the area covered by some Organic and Organic Cryosol map units, is rated as having a high potential to reduce acidity. According to Green (1970), all of this physiographic region is underlain by Mesozoic and some Tertiary clastic sedimentary bedrock. More importantly, however, weakly or moderately calcareous morainal deposits from continental glaciations and associated glaciolacustrine, lacustrine, and glaciofluvial sediments overlie the bedrock and served as the source of soil parent materials over a very large portion of the Plains region. Within this large region, however, there are localized occurrences of glaciofluvial or eolian sands that have low base content. These parent materials may or may not be calcareous. Such areas were given a medium or low rating.

The Foothills region is underlain by Mesozoic and, to some extent, Tertiary clastic sedimentary bedrock. This region has been covered by Cordilleran glaciations of different vintages (Boydell 1972; Roed 1968). The surviving morainal deposits are generally stony, but differ in extent, thickness, and carbonate content. Some of these deposits appear to be sporadically weakly calcareous (Dumanski et al. 1972; Twardy and Corns 1980) and in places shallow or mixed with colluvium. Apparently, bedrock-derived materials have contributed appreciably to the surficial materials. On the basis of the properties of the soils and surficial materials, the acidity reducing potential in this area was estimated to be moderate. From the vicinity of the Bow River and to the south, the glacial deposits appear to be more consistently calcareous, and the acidity reducing potential is estimated to be high.

Ubiquitous glaciations apparently occurred and some are still active in places in the Rocky Mountains region. The resulting deposits are strongly influenced by the bedrock provenance, which varies from extremely calcareous to non-calcareous. The acidity reducing potential is rated high in areas of carbonate rock and rock materials and the related Eutric Brunisol map units derived from the calcareous morainal or colluvial materials. It is estimated to be medium in areas of non-calcareous clastic sedimentary rocks and rock materials and low in the Dystric Brunisol soils on the associated morainal and colluvial materials.

Granite or granite type rocks and associated extremely to very strongly acid sandy Dystric Brunisol soils prevail in the shield area of northeastern Alberta. Their acidity reducing potential is rated as low. The acidity reducing potential of Organic and Organic Cryosol soils was discussed in Section 4.2. Eutrophic systems are rated as high, Mesotrophic as medium, and Oligotrophic as low.

5. PREPARATION OF MAPS OF WESTERN CANADA

By agreement between jurisdictions, each province and territory will prepare and publish their own soil and geology sensitivity maps and accompanying report. Reports may or may not contain copies of the base map but will contain copies of the two interpretive maps.

To conclude the co-operative and co-ordinated effort of Western Canada provinces and territories, a combined report and set of maps will be prepared for Western Canada. British Columbia will be responsible for preparation and publication of this report for soils and geology, with input from and review by jurisdictions. The proposed map scale for compilation of the soil and geology maps for Western Canada is 1:7 000 000.

Completion and publication of reports by provinces and territories is slated for spring 1986. Completion of a draft report and maps for a combined Western Canada report is targeted for mid-May. It is understood that Lands Directorate, Environment Canada is also compiling a Canada-wide map on the theme: "Potential of Soil and Geology to Reduce Acidity of Incoming Acid Deposition."

6. CONCLUSION

Preparation of interpretive maps of soils and geology relative to sensitivity to acid inputs in Western Canada is nearing completion. Though variations in the database exist, sensitivity maps should be consistent due to agreement on consistent rating criteria. Preparation of base maps and sensitivity maps within each jurisdiction has resulted in greater familiarity with the resources within our own boundaries.

It is recognized that revisions of sensitivity maps will be required in the future as the database is improved, as better base maps are prepared, or as rating criteria are revised.

In regard to rating criteria, it must be stated that research is required on the response of soils and geology to acid inputs. Acid input changes in the soil processes already mentioned must be better understood. In particular, the relationships between process changes and effects on vegetation must be investigated.

Future thrusts of the Western Canada Long-Range Transport of Air Pollution Program (LRTAP) has received considerable attention. In regard to terrestrial aspects, establishment of sites for long-term monitoring of soils has been identified as a need. Agreement on sampling and analytical and interpretation methods is still under discussion. Feasibility of sensitivity mapping of vegetation is also being explored.

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LONG-TERM OBSERVATIONS ON SOIL, PLANTS, AND ANIMALS ADJACENT TO A SOUR GAS PLANT IN ALBERTA

by

R.B. Church,[1] K. Smith,[1] and B. Ogilvie[1]

ABSTRACT

In 1961, a large sour gas processing plant came into operation just north of Calgary. A study was initiated downwind on adjacent native range in comparison to a control area which was 4 mi upwind. Soil parameters, plant fauna abundance, and summer cattle production were monitored from 1963 until 1981.

The control and study areas were typical mixed prairie thin black soil, covered by natural climax medium-height grasses in thick sod areas, interspersed with areas of short grasses. Both sites have been used for summer grazing and/or wild hay production since the late 1880s. Neither site has ever been cultivated. The study area was transected to provide soil and plant study sites on S½1.26.29W4 and similar study sites were located on NW¼.12.26.1W5. A single owner pedigree Hereford herd was all wintered west of the plant site, with both the control and study area being utilized for the entire period for cow/calf summer grazing.

The soil pH values in both control and study areas prior to 1970 were in the range of 7.6 to 8.5. Subsequently, a few study sites, closest to the sulphur pile, showed significant drops in pH (pH 4.4 to 5.6). Analysis of soils revealed no significant differences in available phosphorus nitrogen, nitrate nitrogen, selenite, or the amount of organic matter between study and control samples.

The vegetation in the control and study areas was generally similar at the start of the study in 1963. By 1980, plains blue grass, mosses, crocus, everlasting, mallow, three-flowered avens, and buttercup had increased in frequency in the study area compared to the controlled. Significant increases in frequency were noted for the sedges and blue grasses. Western wheat grass, Sandberg grass, fescues, milk-vetch, and shooting star showed a declining frequency in the study area compared with the control area by 1980.

Animal production was measured on the basis of 205-day R.O.P. adjusted weaning weights. Since all cows were wintered and calved together, weaning weights were good indications of the relative production, nutritive value, and palatability of the range grazed in both the control and study areas. In 1971 and 1975, the weaning weights of calves pastured on the study area were significantly lower than for calves weaned off cows from the control area. The cause could not be ascertained with certainty. Several nutritional problems arose during the study which were remedied by management practice which augmented vitamins A, D, and E, and copper and selenium.

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[1] Departments of Medical Biochemistry and Biology, University of Calgary, Calgary, AB

The long-term effects of a large sour gas scrubbing plant on the neighbouring downwind soil, plant, and animal productivity are variable and may take several years to become evident. Unexplained, localized significant drops in soil pH, severe disturbance of vegetation, and lowered weaning weights were observed in some years. No explanation was readily available.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The study area, just north of Calgary, is located within the mixed prairie Thin Black Soil Zone. Both control and experimental areas had a natural climax cover of medium-height grasses in thick sod areas, interspersed with areas of short grasses. The native fauna include June grass and Sandberg's blue grass, interspersed with spear and wheat grasses. The areas also contain small regions of clay-loam saline soil, buffalo wallows, and burnouts. Predominant low-growing species include spike moss, lichens, and sedges. Depending on the past localized grazing history, weedy plants such as crocus, buttercup, prairie sage, fleabane, blackeyed susan, camas, vetch, and buckbrush are found. Both areas have been used for summer grazing or wild hay production since the area was settled in the late 1880's. Continuous ownership by a few ranchers with similar management practices make the control and study areas unique for a comparative study. Neither control or study area has been over-cultivated.

Production technologies developed in the 1950s for sour gas allowed exploitation of the Crossfield and Elkton gas fields on the northern fringe of Calgary. Harold Manley was instrumental in establishing Petrogas Processing Ltd. to produce these gas fields. A sour gas processing plant with an eventual daily capacity of $250 \times 10^6 ft^3$ of gas along with 2000 tons of sulphur (S) was brought on stream on 1961 November 29. The Crossfield field has a 32% hydrogen sulphide content. Initially, the molten sulphur was poured into large blocks. Slatters were installed in 1973, along with increased facilities for tank car transport of molten sulphur.

The late Dr. Bowser of Alberta Soil Survey suggested in 1961 that a long-term study be carried out on the impact of a large-scale gas plant on downwind soil, plant, and animal production, since no such study had been carried out at that time.

2. METHODS AND MATERIALS

In 1961, the control and study areas were both owned and operated by B.C. Church for summer grazing of an R.O.P. pedigree Hereford operation. The study (S½.1.26.29W4) area was immediately downwind, to the east, of the Petrogas plant (W½.2.26.29W4) consisting of some 280 acres of native mixed grass prairie. The 160-acre control area (NW¼.12.26.1W5) was located approximately 3.5 mi. upwind, to the west, of the Petrogas plant. The Church pedigree Hereford herd all wintered on S½9.26.29W4 or parts of sections 1, 11, and 12.26.1W5. All calves were born in a 6-wk calving period, commencing about March 01 each year on the home ranch (sections 1 and 12.26.1W5). Groups of between 25 and 35 cows and calves, in recorded sire breeding units, were moved to various separate summer pastures, including the study and control areas, in mid-June each year. Cows and calves were moved onto stubble or covercrop at various locations after harvest, usually in mid- to late October. All calves were weighed at weaning and 205-day R.O.P. records maintained. After weaning, both bull and heifer calves were wintered on a silage, hay, and concentrate ration. Superior performance male and female calves were kept for breeding stock and the remainder of the calves were fed out to slaughter weight in the feedlot at the home ranch.

The study area was transected to provide 48 soil and plant study sites on the 280 acres of the S½.1.26.29W4. Forty-eight similarly placed soil and plant study sites were located at the 160 acres of the control area, NW¼.12.26.1W5.

Soil samples were taken on the prescribed grid in 1963 and most years, subsequently utilizing standard procedures of Alberta Soil Survey for classification and analysis (Alberta 1956). Samples were taken with a 24-in. soil sample tube and sealed in a plastic tube.

Plant fauna surveys were carried out by utilizing 2-yd^3 grids at each of the designated sample sites.

Unfortunately, Turbo Resources purchased Section 1.26.29W4 and subsequently stripped the study area topsoil before construction of a refinery which came into operation in 1984.

3. RESULTS AND DISCUSSION

The profile of soil cores taken from the study and control areas were within that expected for soil classified within the Thin Black Soil Zone. The A horizon varied from 2 to 8 in. in depth, and from dark brown to deep black in colour. In most soil core samples, a clear B horizon of some 6 to 10 in. was noted. The Ck or lime horizon occurred at depths of from 12 to 16 in. below the surface. There were areas of saline soils associated with blowouts, creek, or slough edges in the area. By chance, none of the sample sites fell within these minor variations. The range of pH observed over the years is presented in Table 1.

The pH value is indicative of the relative availability of elements in the soil. At pH below 5, availability of nutrients is greatly reduced, with the exception of iron (Truog 1949). Since the normal pH of the soils studied was in the 8 range, where manganese, copper, zinc, and iron are normally in a less readily available form in the soil, the significance of a 4 unit change in pH should have a dramatic effect on plant nutrient availability under native range conditions with 10 to 14 in of annual rainfall.

The effect of pH on the soil microfauna was not analyzed; however, since the optimal pH for growth of different species is different, significant changes could be expected for those species with narrow tolerances in pH optima.

In the tissues of all plants, the absorption of substrate ions is inhibited by competing ions. The degree of competition varies between ions in the soils examined in this study due to the inherent high concentration of calcium (Epstein and Rains 1965). Secondly, the competition between SeO_4^{2-} and SO_4^{2-} should be examined where a heterologous source of S is introduced. The dissolved mineral nutrients of soils are not uniformly distributed in the aqueous phase due to aggregation and charge effects between ions and particles. The chemical analysis of the soil solution, obtained by inference from analysis of extracts, or other means, will be examined in another paper. Suffice it to say that the advent of ion-selective electrodes provided an alternative to spectrophotometric and colourimetric techniques for measurements of ions directly in a solution in equilibrium and in contact with soil particles. The limitations imposed by imperfect selectivity remain a problem. The effect of soil moisture, mineral element composition, and biologic activity provide a complex problem which is not easily amenable to experimental attack.

Sulphides form under anerobic conditions in soil and the free hydrogen sulphide formed is toxic to plants at low concentrations (Allen et al. 1972). In agreement with Lowe (1969), our attempts at measuring soil sulphur have not been satisfactory using the LECO combustion and sulphur

Table 1. Summary of soil pH ranges.

Year	Control Area	Study Area
1963	7.8 to 8.4	7.8 to 8.3
1967	7.8 to 8.3	7.6 to 8.5
1970	7.7 to 8.4	5.6 to 8.3 (3)[a]
1972	7.6 to 8.2	5.5 to 8.4 (4)[a]
1975	7.6 to 8.2	5.5 to 7.9 (1)[a]
1978	7.8 to 8.4	5.1 to 8.0 (1)[a]
1980	7.7 to 8.4	4.6 to 7.8 (11)[b]
1981	7.6 to 8.3	4.4 to 8.0 (14)[b]

[a] ( ) number of sites closest to sulphur storage pile which were subject to heavy localized sulphur deposits as a result of high chinook winds during loading.

[b] ( ) number of sample sites with a pH more than 1 unit below 7.5.

dioxide titration method. Problems arise from the fact that S is converted to SO_2 and SO_3 which were not recovered quantitatively in our analysis.

The analysis of soils revealed no significant differences in available phosphorus, nitrate nitrogen, salinity, or the amount of organic matter between study and control samples.

The vegetation in the control and study areas was very similar (Table 2). Each area had a history of well-managed summer range or native hay production. Native hay was normally cut every 2 or 3 years depending on moisture levels. It is significant that both areas contained some of the best undisturbed native mixed prairie grasslands found in the Calgary area. The vegetation in 1963 was mainly June, blue, Sandberg, spear, and wheat grasses overgrowing spike mosses, sedges, and lichens. In both the control and study areas, one or two sample sites contained blue grama. A few sites contained fescue and rye grasses. It is interesting that the blue grama, plains blue, and Western wheat grass had disappeared from the study area by 1970. These grasses appear to have been replaced by increased numbers of Canby blue grass sedges and annual blue grass. Most species showed no change. The vastly increased predominance of sedges and annual blue grass in the study area represents a significant decrease in palatability and nutritional value of the forage available for grazing. Of the native legumes, only milk vetch showed sensitivity. However, alfalfa in a neighbouring hayfield seeded to brome and alfalfa declined rapidly.

The ultimate production on a ranch is the productivity of cows through the weight of calf weaned. Table 3 presents data from alternate years for 205-day R.O.P. adjusted weaning weights. Since all cows were together after weaning, over the winter, and from calving until June 15, the weaning weights are a good indication of the relative production, nutritive value, and palatability of the range on which they grazed over the summer. In both 1971 and 1975, the weaning weights of calves run on the study area were significantly lower than for calves from the control area. The cause could not be ascertained with certainty. No significant differences were noted for 365-day R.O.P. weights.

Several nutritional problems arose during this study. In 1971, several calves were diagnosed by the Provincial Veterinary Laboratory as being selenium deficient. The results could not be analyzed in subsequent

Table 2. Relative abundance of some plant fauna.

Species	Control Area[a]	Study Area[a]
Plains blue grass	0	+
June grass	0	0
Western wheat grass	0	-
Other wheat grass	0	0
Spear grass	0	0
Sandberg grass	0	-
Blue grass	0	0
Blue grama	0	-
Lichens	0	0
Spike moss	0	+
Sedges	0	++
Fescues	0	-
Rye grass	0	0
Canby blue grass	0	++
Fleabane	0	0
Blackeyed susan	0	0
Crocus	+	+
Milk-vetch	0	-
Camas	0	+
Prairie sage	0	+
Buckbrush	0	0
Gaillardia	0	0
Everlasting	-	+
Shooting star	+	-
Violet	0	0
Mallow	0	+
Buffalo bean	0	0
Prairie cinquefoil	0	0
Three flowered avens	0	+
Buttercup	0	+
Annual blue grass	0	++

[a] 0 = no change 1963 to 1980.
+ = increase 1963 to 1980.
- = decrease 1963 to 1980.

Table 3. Comparative weaning weights of calves.

Year	Control Area[a]		Study Area[a]	
	Males	Females	Males	Females
1963	480	450	485	460
1965	520	490	515	480
1967	535	505	530	500
1969	540	510	545	515
1971	555	505	405	390
1973	575	500	580	560
1975	565	530	500	475
1977	555	510	555	515
1979	580	565	575	570
1981	585	560	580	515

[a] Calves born in March at the home ranch were placed on the control or study area with their mothers in single-sire breeding units June 15th of each year. Weaning weights are the 205-day R.O.P adjusted average weights. Cows and calves were wintered upwind from plant at the home ranch. Cows were assigned to one of five breeding units in different pasture at any given year.

years as vitamins A, D, and E and selenium were injected postpartum on a regular basis as a management practice for all cattle.

Secondly, in 1981, the first case of copper deficiency occurred in a herd located adjacent to the study area. Animals exhibited a unique cracking pattern of the hoof, a 'burnt', dead look to their hair, and a general unthriftiness. All cattle in the test herd had been fed a special trace mineral fortified salt mixture since 1971, hence, no copper or selenium deficiency syndrome has been recorded since that time.

4. GENERAL OBSERVATIONS

Several interesting, unexplained observations have been made in the study area over the years.

1. It was not unusual in the early years of block pile sulphur handling to observe elemental sulphur a mile downwind from the pile during a chinook. In fact, just outside the study area toward the plant, so much contamination occurred that all vegetation was killed in certain areas. Subsequently, high application of lime raised the pH of these barren areas from 2.8 to 6.4. Vegetation has now been re-established in these areas.
2. From 1970 onwards, small areas of 2 to 6 yd^2 were observed up to 1 mi from the plant on which no vegetation grew for at least one growing season. The cause was not identified.
3. In 1964, a new fence was built 1 mi east of the plant. Half of the wire was domestic and half imported. Within 2 months, after construction, the imported wire had a very definite rusted appearance.
4. From 1971 onwards, the cattle progressively quit grazing close to the plant. Apparently, the less palatable species were becoming predominant. As well, in dry spells, the sulphur dust on the vegetation was sufficient to irritate an animal's eyes during grazing.
5. There have been dramatic changes in the amount of elemental sulphur which was blown off the Petrogas site since the

slatters were installed in 1973. Petrogas has been an excellent corporate neighbour who has shown great concern for its neighbours over the years.

5. SUMMARY

The long-term effects of a large sour gas scrubbing plant on the neighbouring downwind soil, plant, and animal productivity have been studied. The results to date suggest:

1. Effects on soil may take up to 20 yr to show up in soil with a strong lime horizon. However, pH can change up to 4 pH units in 1 yr, presumably after buffering capacity of the lime horizon has been utilized.
2. The fauna distribution of plant species in unfertilized native mixed prairie ranges can change dramatically. There is an increase in less productive and less palatable forage species at the expense of more productive and palatable species.
3. Livestock production can be affected dramatically. in addition to enhancing the potential for selenium and copper deficiency in cattle, significant unexplained decreases in weaning weights can be experienced in some years.

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VARIABILITY IN FOREST SYSTEMS AS IT RELATES TO ELEMENTAL SULPHUR EFFECTS

by

D.G. Maynard[1] and P.A. Addison[2]

ABSTRACT

A 5-year project was initiated in 1981 to study the effects of sour gas processing on the forest ecosystem in west-central Alberta. A biomonitoring network was established in a 30- x 30-km area surrounding the Strachan and Ram River sour gas plants. In addition, detailed studies were initiated to determine the mechanisms and magnitude of the particulate elemental sulphur (S^0) impact on the soils and vegetation of the area. This paper reports on some of the results of this study, and the quantification of variability associated with these ecological measurements and its influence on biomonitoring.

A technique was developed to determine elemental sulphur (S^0) in soils and to estimate S^0 deposition. Deposition at sites adjacent to the gas plant was found to be considerably less than the deposition that must have occurred previously to produce the S^0 concentrations present in the surface organic horizon (LFH). Significant changes in soil chemical properties and plant cover were observed at these sites impinged with heavy concentrations of S^0. However, changes at sites impinged with low concentrations of S^0 (<5000 $\mu g \cdot kg^{-1}$) were more difficult to assess.

Random or natural soil variability ranged from 24 to 102% on a regional basis. Spatial variability was the largest component of the partitioned variability; however, there was a significant regional component as well. For the soil parameters measured, temporal variability was generally not significant. Because of the high variability, concentration differences, in the order of 50% or greater, were needed to be considered significant. Plant cover estimates measurement error was high (20%), and changes in plant cover between sampling times would have to exceed 20% before interpretation would be possible. Growth measurements were equally variable.

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[1] Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB

[1] Canadian Forestry Service, Ottawa, ON

1. INTRODUCTION

The Canadian Forestry Service has been involved with air pollution research in Alberta for the past 15 years. During that time, our role has been to provide both industry and provincial regulatory agencies with scientific information upon which decisions, with respect to forest management, could be made. In 1981, we initiated a project upon a request from Canterra Energy Ltd. (then Aquitaine Company of Canada) and Gulf Canada Resources Inc. into the effects of sour gas processing on the forest ecosystem. This project had two objectives:

1. To establish and describe a biomonitoring network to detect and quantify the effects of sour gas processing on forest systems in the vicinity of Ram River and Strachan gas plants; and
2. To determine the mechanisms and magnitude of particulate elemental sulphur (S^0) impact on the soil and plant components of the forested ecosystem.

In order to accomplish these two objectives, a number of new techniques had to be developed that were sufficiently precise to give us confidence in the results. Obviously, variability in both the natural system and the measurement techniques must be quantified before one can trust any technique. It is the quantification of variability in ecological measurements and its influence on biomonitoring that is the central theme of this paper.

The area under investigation was west-central Alberta where the Ram River (largest gas plant in the province) and Strachan (10th largest) sour gas plants are located. The forests of the area are dominated by lodgepole pine with co-dominants of aspen and spruce in various locations. The soils of the area are predominantly Brunisolic and Podzolic Gray Luvisols.

The results from the initial survey and the characterization of 26 sites in the area are synthesized in Addison et al. (1984). The results of that study and the more detailed work that followed demonstrated that certain sites had been heavily impinged by elemental sulphur. The rate of deposition, however, slowed considerably between 1982 and the present. These sites had measurable differences in soil chemical properties, and the response of plants in the understory was dramatic. In 1981, trees did not show either a growth or reproduction response even though tissue sulphur (S) content was elevated.

The question that this paper attempts to address is: What evidence is required to make the above statements, and how can we collect such data when techniques are not precise and variability in the natural ecosystem is great? We hope that, through the use of examples centred around our study into the effects of elemental sulphur on a forest, some light will be shed on the subject.

2. DEPOSITION

We know from the extremely high concentrations of total S in the surface organic horizon (LFH) that heavy deposition of S^0 has occurred at sites adjacent to the S^0 blocks. However, since S^0 was a major pollutant in the forest adjacent to the sour gas plants, a direct measurement of S^0 in organic surface soils was required.

The precise measurement of S^0 in biological systems is difficult and few attempts have been made to carry out such assays (Roy and Trudinger 1970). None of the methods described in the literature measured S^0 in soils or sediments containing high amounts of organic matter. The determination of S^0 in acetone extracts, originally proposed by Hart (1961), was neither accurate nor sensitive enough for organic forest horizons, giving values about 50% too high at 1000 mg•kg^{-1} S^0. The use of organic solvents, such as carbon disulphide (CS_2), as suitable extracts was rejected since one form of S^0 (fresh prills) produced at the sour gas plants was either totally or partially insoluble in CS_2 after 24 h. Therefore, a method was proposed (Maynard and Addison 1985) using an acetone extract (as described by Hart 1961) and a colourimetric determination of S^0 as thiocyanate following the procedure of Bartlett and Skoog (1954). Interferences due to the coloured extract gave absorbance readings equivalent to 10 to 15 mg•kg^{-1} S^0 in moist soils, even after blank correction. A detection limit was defined as 100 mg•kg^{-1} S^0. Recoveries of added S^0 varied from 90 to 104% in soils containing 100 to 50 000 mg•kg^{-1} S^0, and the precision was about ±3% using 95% Confidence Limit (C.L.) as a percentage of the mean at 1000, 10 000, and 50 000 mg•kg^{-1}.

With this method, we were able to determine whether a site had been impinged with S^0 in excess of 100 $mg \cdot kg^{-1}$ with a high degree of confidence. Elemental sulphur is not normally present in surface aerobic soils (Freney and Williams 1983), and the presence of any S^0 in the LFH indicated deposition of S^0 had occurred. Total S concentrations, on the other hand, ranged from 900 to 1500 $mg \cdot kg^{-1}$ in the LFH horizons of this region (Addison et al. 1984), and increases in the order of 500 $mg \cdot kg^{-1}$ would be required (see discussion below) to be 90% confident that significant deposition ($p<0.05$) had occurred. For sites heavily impinged with S^0 deposition, either total S or S^0 measurements would be suitable. However, despite total S measurements being more precise than S^0 determinations (Hogan and Maynard 1984), increases in the total S concentration, owing to S^0 deposition amounting to <500 $mg \cdot kg^{-1}$ S, could not be detected on a regional basis (see discussion below).

In the introduction, it was suggested that the majority of the deposition had occurred prior to the initiation of our study in 1981. During June to October 1982 and April to October 1983, deposition of S^0 to the soil surface was measured at three sites, 50, 200, and 500 m from the S^0 block at Strachan. Ten replicates of a 132-cm^2 plastic container with a terry-towel fabric were placed at the soil surface. The towelling was used to provide a rough surface to prevent the S^0 from moving, and also it provided a material that, when extracted, did not produce any colour interferences to the S^0 method. The material was changed every 2 wk and the towelling extracted with acetone and S^0 determined as discussed above. The method could detect 1 $mg \cdot L^{-1}$ of S^0 in solution equivalent to a detection limit in kilograms per hectare of 0.08 $kg \cdot ha^{-1}$ S^0. Ten replicates were measured at each site for each sampling.

The S^0 deposited over the two growing seasons (1982 and 1983) accounted for <10% of the total S^0 in the LFH. An example of the deposition rate compared to the S^0 in the LFH horizon during one deposition period, July 1982, is given in Table 1. The S^0 deposited during July 1982 accounted for <2% of the total S^0 in the LFH at the most heavily contaminated site. Deposition at the site 500 m from the S^0 source was 1.3 $kg \cdot ha^{-1}$ (equivalent to approximately 40 $mg \cdot kg^{-1}$), and would not be detectable in the soil by either total S or S^0 measurements. The coefficient of variation (CV) for the S^0 deposition rate was in the order of 15 to 25% per sampling period. Most of this error was associated with the particulate deposition through the canopy and was not related to the technique.

Deposition rates in the same order of magnitude as July 1982 were observed throughout the 2 years that deposition was monitored. This indicated that the deposition rates of S^0, that resulted in the extremely high S concentrations of the LFH adjacent to the S^0 block, occurred prior to 1982 when mechanical breakup of the S^0 blocks took place. Deposition of S^0 was still occurring, but at a much lower rate. However, significant changes in the total or S^0 concentrations of the LFH were not observed between 1982 and 1984, owing to the large variability of the sulphur measurements. In addition, the leaching of the SO_4^{2-}-S produced from the oxidation of S^0 occurred at a rate in the same order of magnitude as the deposition rate (Table 1).

3. SOILS

The results from the initial survey and the characterization of the soils in the area surrounding the sour gas plants were presented elsewhere (Addison et al. 1984). It was found that four sites had been impinged by S^0, and that three of the four showed significant changes in certain chemical properties. These changes were obvious owing to the heavy deposition of S^0. However, where deposition of S^0 or SO_2 was considerably lower and the changes in soil parameters more subtle, the variability of the parameters to be measured had to be quantified before it could be determined if there were any significant changes.

The variability associated with a given soil parameter can be either analytical or random. Analytical variability is determined by the precision of the technique used and determines the magnitude of the change that can be detected. In assessing the variability of soil parameters in forest soils, the analytical variability is usually not a factor compared to the random variability. For example, the precision for the S^0 determination in LFH was approximately ±3%, whereas the random variability associated with the S^0 concentrations in the LFH exceeded 30%.

The random variability of several soil parameters was assessed using a nested or hierarchical sampling scheme to distinguish variation

Table 1. Deposition of elemental S and leaching of S at the Strachan sour gas plant in July 1982 in relation to the total and elemental S of the LFH horizon (± standard deviation).

Distance from Source (m)	Deposition[a] of S^0	Leaching[b] of S	Total[a] S	Elemental[a] S
	(--------------------	kg·ha^{-1}	--------------------	-------------------)
50	40.5 ±6.1	95 ±54	2170 ±1650	2070 ±1600
500	1.3 ±0.3	16 ± 7	270 ± 150	230 ± 110

[a] n = 10

[b] Total S in the leachate from zero tension lysimetres below the LFH horizon (n = 5).

derived from two or more levels of subdivision of a population (Webster 1985). This approach has been used successfully in describing the variability of various parameters in forest soils (Hammond et al. 1958; Ike and Clutter 1968).

In order to determine the regional variability, the biomonitoring sites described by Addison et al. (1984) were used. In 1981, 26 sites were established in even-aged *Pinus contorta Dougl.* var. *latifolia Engelm.* stands in an area 30 x 30 km that had two sour gas processing plants at the centre (Addison et al. 1984). Site locations were based upon available air quality and airflow information, topography, logistics, and accessibility. The sites were subsequently divided into three groups: (1) sulphur-dusted; (2) sulphur gas-exposed; and (3) background. Sulphur-dusted sites had measurable (>100 $mg{\cdot}kg^{-1}$) S^0 present. The sulphation isopleth of 0.05 $mg{\cdot}dm^{-2}{\cdot}d^{-1}$ (SO_3) was chosen to delimit the area of gas impingement. The threshold is arbitrary and is 10% of the provincial exposure guideline.

Four sites had measurable S^0 in the surface horizon and were eliminated from the variability portion of the study as significant differences in soil chemical properties had been observed (Addison et al. 1984). At each site, a 20- x 20-m plot was established with a north-south orientation. Five soil pits were dug and samples from each of the four surface horizons were collected. The samples were analyzed for pH and total Ca, Mg, K, Mn, Al, Fe, S, and P by inductively coupled plasma atomic emission spectrometry (ICP-AES) following a HNO_3, $HClO_4$, and HCl digestion (Hogan and Maynard 1984). Ammonium acetate (NH_4OAc) extractable concentrations of the above elements were also determined by ICP-AES.

A single factor analysis of variance (ANOVA), Model II (random effects), was used (Neter and Wasserman 1974). There were 22 factors (sites) with five observations (pits) per factor. Estimations of the variability of the various chemical analyses, and the proportion of the total variability of these parameters that is accounted for by differences among the plots, can be obtained by calculating an ANOVA, as shown in Table 2, for each of the measured soil variables and for each soil horizon.

To assess the temporal variability, a site, 750 m from the gas plant, was chosen. The site was sampled 13 times over 3 years (1982 to 1984), between the months of April and October. Ten replicate samples from

Table 2. A single-factor Model II ANOVA for the regional and temporal variability studies.

Source of Variation	SS	df	MS	E(MS)	F
Between sites	SSTR	r-1	MSTR	$s^2 + n's_t^2$	MSTR/MSE
Error (within sites)	SSE	r(n-1)	MSE	s^2	
TOTAL	SSTO	nr-1			

the LFH horizon were collected at each sampling time. The samples were analyzed for total and 1.0 M NH_4Cl extractable Ca, Mg, K, Mn, Al, Fe, P, and S, as described above. The site was selected because it was representative of the soils and vegetation in the area, and was thought to have a minimal amount of S^0 contamination. There were, however, significant amounts of S^0 present and, because of this, the S values are higher than would be expected. The Ca concentrations are not presented for this site because a portion of the site was limed in 1984.

A single factor analysis of variance, as shown in Table 2, for the regional variability was again used to partition the temporal variability. There were 13 factors (sampling dates) with 10 observations per factor.

A final experiment was carried out at three sites: (1) a site with no measurable S^0; (2) a site with low levels of S^0 (approximately 5000 $mg \cdot kg^{-1}$); and (3) a heavily impacted site (approximately 47 000 $mg \cdot kg^{-1}$) adjacent to a sour gas plant. A one-time sampling was done, with 50 samples from the LFH horizon taken to assess the spatial variability and to determine the effect of S^0 on the elemental concentration of the LFH horizon. Total and 1.0 M NH_4Cl extractable concentrations of Mg, K, Mn, Al, Fe, P, and S were determined, as described above, in addition to pH (5:1 water to soil ratio) and electrical conductivity (EC). Calcium was not included because two of the sites had been limed.

The regional variability of the total concentrations in the LFH horizon is given in Table 3. All the elements, except Mn, showed that regional variability was highly significant. The overall variability [as expressed by the coefficient of variation (CV)], ranged from 24 (for S) to 102% (for Mn), of which between 11 and 50% of the variance was accounted for by the variance among sites. The high overall variability associated with Mn (and to a lesser extent Fe) could possibly be related to sampling errors in separating the mineral soil from the LFH. Small amounts of mineral contamination could change the concentration of these elements. The proportion of the Mn variability, accounted for by the differences among sites, was not significant, although the overall variability for Mn was considerably higher than for any other element. The large variability of Mn within site probably obscured any regional variability.

Table 3. Regional variability of the total nutrient content in the LFH horizon.

Parameter	Mean ± std dev (CV) ($mg \cdot kg^{-1}$)	Significance[a]	Variance Ratio[b]
Ca	5050 ± 2180 (43)	*	33
Mg	1190 ± 410 (34)	*	50
K	2160 ± 530 (24)	*	29
Mn	1160 ± 1180 (102)	NS	11
Fe	3730 ± 1910 (51)	*	32
P	1080 ± 290 (27)	*	35
S	1060 ± 260 (24)	**	19

[a] *, **, NS = Significant at $p<0.001$ and 0.01 and not significant, respectively, for differences among sites.

[b] Ratio of the variance among sites over the total variance. This ratio measures the proportion of the total variability that is accounted for by the differences among the sites.

The regional variability of the extractable nutrients is given in Table 4. The overall variability associated with the extractable nutrients is generally higher than for the total concentrations. Similar comparisons between total and extractable nutrients in forest soils have been observed elsewhere (Grier and McColl 1971; Arp and Krause 1984). The amount of total variance accounted for among sites (regional variability), however, is generally less for the extractable concentrations than for the total concentrations.

The minimum difference required to show significance ($p<0.01$, 0.05, and 0.10 at 80 and 90% certainty) between two sites, for total S and Mn concentrations in the LFH, are given in Tables 5 and 6, respectively. The differences were calculated according to Sokal and Rohlf (1981) from the data of the regional study (22 plots with 5 observations per plot). A typical level of significance for a field study might be considered $p<0.05$ with 90% certainty. A minimum difference of 540 $mg \cdot kg^{-1}$ S would be needed for that difference between two sites to be significant at the 0.05 level with 90% certainty, approximately a 50% change in S. For Mn, a difference of 2450 $mg \cdot kg^{-1}$, or a 211% change, would be required for the difference to be significant at the same level and certainty. The other elements would require a difference between 50 and 200% of the mean to be significant.

The temporal variability of the total elements in the LFH horizon is given in Table 7. This site was contaminated with approximately 5000 $mg \cdot kg^{-1}$ S^0; however, with the exception of total S, the mean concentrations are similar to those for the region. The proportion of the total variability that can be accounted for by the differences among sampling times is only significant for Mn and Al. In fact, the ratio of the variance among times over the total variance is <10% for all the elements except Mn. Therefore, it appears that, for total nutrients in the LFH, temporal variability is not a major concern. Similarly, for the extractable nutrients (Table 8), temporal variability is only significant for two elements (9 and 12%, for P and Mg, respectively) other than S. Extractable S was a special case because the site was impinged by S^0 and oxidation of S^0 to SO_4^{2-} -S had occurred. This resulted in significant ($p<0.05$) temporal fluctuations of extractable S; however, the changes are directly attributable to the deposition of S^0 and its subsequent oxidation. In contrast, to the temporal

Table 4. Regional variability of the 1.0 M NH_4OAc extractable nutrient content in the LFH horizon.

Parameter	Mean ± std dev (CV) ($mg \cdot kg^{-1}$)	Significance[a]	Variance Ratio[b]
Ca	4810 ± 2600 (54)	*	18
Mg	600 ± 240 (40)	**	38
K	980 ± 400 (41)	NS	7
Mn	310 ± 220 (71)	*	22
Al	150 ± 130 (87)	**	50
Fe	13 ± 16 (123)	NS	8
S	170 ± 66 (39)	NS	8

[a] *, **, NS = Significant at $p<0.01$ and 0.001 and not significant, respectively, for differences among sites.

[b] Ratio of the variance among sites over the total variance. This ratio measures the proportion of the total variability that is accounted for by the differences among the sites.

Table 5. Minimum differences for the total S of the LFH required to be significant between two sites.[a]

Level of Significance	90% Certainty			80% Certainty		
	0.01	0.05	0.10	0.01	0.05	0.10
Samples per Plot (n)	(----------	----------	---------- mg•kg^{-1}	----------	----------	----------)
2	1080	880	790	960	760	670
5	640	540	490	570	470	410
10	450	380	340	400	330	290
20	320	270	240	280	230	200

[a] In all cases, it is assumed that the number of plots is 22, according to the regional variability study. Mean S concentration in LFH from the regional variability study was 1060 ± 260 mg•kg^{-1}.

Table 6. Minimum differences for the total Mn of the LFH required to be significant between two sites.[a]

	90% Certainty			80% Certainty		
Level of Significance	0.01	0.05	0.10	0.01	0.05	0.10
Samples per Plot (n)	(------ $mg \cdot kg^{-1}$ ------)					
2	4900	4020	3590	4350	3470	3040
5	2920	2450	2210	2590	2120	1870
10	2040	1710	1540	1800	1480	1310
20	1440	1210	1090	1280	1050	930

[a] In all cases, it is assumed that the number of plots is 22, according to the regional variability study. Mean Mn concentration in LFH from the regional variability study was 1160 ± 1180 $mg \cdot kg^{-1}$.

Table 7. Temporal variability of the total elements in the LFH horizon.

Parameter	Mean ± std dev (CV) ($mg \cdot kg^{-1}$)	Significance[a]	Variance Ratio[b]
Mg	875 ± 310 (35)	NS	2
K	1930 ± 616 (32)	NS	6
Mn	1080 ± 680 (63)	*	13
Al	5630 ± 2750 (49)	**	9
Fe	2920 ± 1490 (51)	NS	6
P	1040 ± 205 (20)	NS	0
S	6940 ± 3420 (49)	NS	0

[a] *, **, NS = Significant at $p<0.05$ and 0.01 and not significant, respectively, for differences among sites

[b] Ratio of the variance among sites over the total variance. This ratio measures the proportion of the total variability that is accounted for by the differences among the sites.

Table 8. Temporal variability of the 1.0 M NH_4Cl extractable nutrients in the LFH horizon.

Parameter	Mean ± std dev (CV) ($mg \cdot kg^{-1}$)			Significance[a]	Variance Ratio[b]
Mg	280	± 113	(40)	*	12
K	1050	± 436	(41)	NS	1
Mn	282	± 186	(66)	NS	0
Al	71.5	± 132	(182)	NS	0
Fe	6.7	± 5.7	(85)	NS	0
P	111	± 63	(57)	*	9
S	525	± 369	(71)	**	17

[a] *, **, NS = Significant at $p<0.05$ and 0.01, and not significant, respectively, for differences among sites.

[b] Ratio of the variance among sites over the total variance. This ratio measures the proportion of the total variability that is accounted for by the differences among the sites.

variability results of this study, Palmer et al. (1985) found that temporal variability was a very significant component of the overall variability of pH in several Alberta soils. The reasons for the differences in temporal variabilities between these studies are unknown, but it clearly demonstrates the need to evaluate the variability for each soil factor on the soils to be monitored.

The spatial variability of three sites: (1) an uncontaminated site; (2) a site with a moderate concentration of S^0 in the LFH (approximately 5000 $mg \cdot kg^{-1}$ S^0); and (3) a heavily contaminated site (approximately 48 000 $mg \cdot kg^{-1}$ S^0), was determined. The pH and electrical conductivity (EC) of the LFH horizon for the three sites are given in Table 9. Only the most heavily impinged site (Site 3) had significant decreases in pH and increases in EC in the LFH horizon compared to the unimpinged site (Site 1). The uncontaminated site and the moderately contaminated site also had similar total and extractable concentrations for Mn, Mg, K, and P (Tables 10 and 11). In general, these concentrations were similar to the regional concentrations. At Site 3 (heavily impinged site, adjacent to the sour gas plant), the total and extractable concentrations of Mg, K, P, and Mn were significantly reduced. This site was also an area of low pH (Table 9), indicating these cations and P were more readily solubilized and leached. In contrast, Fe and Al increased significantly at the most heavily impinged sites. This was probably a result of increased activity at these sites owing to their proximity to the sour gas plants. Increased activity would result in additions of mineral particulate to the LFH horizon that could increase the Fe and Al concentrations, owing to the high concentration of these elements in the mineral soils of this area.

The spatial variability of the elements measured at the heavily contaminated site was surprisingly similar to the variability observed at the other two sites, with the exception of S. As indicated earlier, the increased variability in S was related to the deposition of the particulate S^0 through the canopy. Manganese was the most variable element but it also showed the largest response to S^0 deposition, decreasing 20-fold to <50 $mg \cdot kg^{-1}$ in the LFH at the most heavily contaminated site.

The results of the deposition and soil data indicate that very high concentrations of S^0 have been deposited into the forest within 500 m of the

Table 9. Spatial variability of pH and electrical conductivity (mS•cm^{-1}) of the LFH horizon at three sites.

Site	pH			Conductivity		
(mg•kg^{-1} S^0)	Mean ± std dev*		%CV	Mean ± std dev		%CV
1 (no S^0)	4.3 ± 0.3	b	7	0.4 ± 0.1	a	25
2 (5 000)	4.5 ± 0.8	b	18	0.7 ± 0.2	a	28
3 (47 000)	2.5 ± 0.4	a	16	4.1 ± 1.4	b	34

One sampling in August 1984 (n = 50).

*Means in each column followed by the same letter do not differ significantly at $p \leq 0.05$.

Table 10. Spatial variability of the total nutrient concentrations ($mg \cdot kg^{-1}$) of the LFH horizon at three sites.

Site	Mg	K	Mn	Al	Fe	P	S
1	838 ± 198a*	1840 ± 500b	750 ± 420b	3750 ± 1400a	2080 ± 1140a	1070 ± 173c	1 040 ± 140a
2	862 ± 294a	1780 ± 430b	1020 ± 760c	5450 ± 2480b	2790 ± 1320b	937 ± 185b	5 720 ± 1 920b
3	1040 ± 611a	1140 ± 400a	48 ± 24a	5270 ± 2290b	3340 ± 1310b	616 ± 146a	47 700 ± 14 100c

One sampling in August 1984 (n = 50).

*Means in each column followed by the same letter do not differ significantly at $p \leq 0.05$.

Table 11. Spatial variability of the extractable concentrations (mg•kg^{-1}) of the LFH horizon at three sites.

Site	Mg	K	Mn	Al	Fe	P	S
1	565 ± 167c*	1460 ± 480c	572 ± 240b	80 ± 39a	9 ± 5a	138 ± 47c	97 ± 37a
2	248 ± 77b	945 ± 295b	564 ± 410b	82 ± 110a	12 ± 13a	54 ± 39b	390 ± 140b
3	327 ± 155a	184 ± 44a	30 ± 20a	108 ± 74a	143 ± 98b	26 ± 14a	3850 ± 2100c

One sampling in August 1984 (n = 50).

* Means in each column, followed by the same letter do not differ significantly at $p \leq$ at 0.05.

two sour gas plants. Significant changes have occurred in several of the soil chemical properties measured at these sites. Total and extractable concentrations of Mg, K, Mn, and P in the LFH horizon have decreased, along with decreases in the pH and increases in the EC. Iron and aluminum concentrations tended to increase. However, changes in these soil properties at sites with low level deposition of SO_2 or S^0 are much more difficult to assess. At Site 2 (approximately 5000 $mg \cdot kg^{-1}$ S^0 in the LFH horizon), moderate concentrations of S^0 have been deposited for a minimum of 4 years. Significant differences in chemical properties, such as pH, Mn, and the basic cations, between Site 2 and Site 1 (unimpinged site) were not found. In a laboratory study, 1000 $mg \cdot kg^{-1}$ of S^0 was applied to LFH material and the soil incubated for 28 wk (unpublished results this laboratory). In 8 wk, the entire 1000 $mg \cdot kg^{-1}$ of S^0 had oxidized to sulphate; however, no changes in the pH or extractable cations were observed. This suggests that the LFH horizon in this area has the ability to buffer additions of acid.

Spatial variability was the largest component of the overall variability; however, there was a signficant regional component. For example, the regional variance of S accounted for 19% of the total variance, and the difference required to be 90% confident at the 0.05 level of significance would be reduced from 540 $mg \cdot kg^{-1}$ (when the spatial and regional components were included) to approximately 480 $mg \cdot kg^{-1}$ (when the regional component is removed). In contrast, temporal variability for the elements measured in this study was generally not significant.

The variabilities of the various elements observed in this study are similar to the variabilities found in LFH horizons for other forest systems (Grier and McColl 1971; Quesnel and Lavkulich 1980; Arp and Krause 1984) and do provide a general assessment of soil variability. However, it is important that the variability of a given technique or measurement should be evaluated for the soils of an area prior to the establishment of any long-term soil monitoring sites.

4. PLANTS

Although visual estimates of plant cover are among the most common measurements made in plant ecology, errors in measurement are rarely quantified. Error analysis is imperative in repetitive sampling for biomonitoring because systematic error in the measuring technique must be quantified before changes in vegetation can be determined. Although sources of error have been outlined by Cain and de Oliveira Castro (1959), Greig-Smith (1964), and Kershaw (1973), only Sykes et al. (1983) have determined the magnitude of errors when different quadrat sizes and several observers are used.

In order to determine the precision of the cover estimates, 20 randomly distributed 1- x 1-m quadrats were permanently established in a 20- x 20-m site. A visual assessment of the percentage cover of every understory species in each quadrat was performed nine times between 09 and 19 August 1982 by the same observer. No variation in the vegetation was apparent during this 11-day period. To minimize observer bias, the order in which the quadrats were examined was varied, the work was interspersed with other tasks, observer access to the data was restricted, and the observer was discouraged from discussing the project.

Consistent measurements were obtained when the observer was thoroughly familiar with the vegetation and had described several similar stands prior to initiating this experiment. Despite the attempts to have the observer not remember specifics about the plots, there is an obvious familiarity period in the repetitive measurements made over the 9-day period. The precision improved as the observer's familiarity with the vegetation increased, as is reflected in Table 12. Measurements made 1 day apart towards the end of the 9 days were 94 to 96% similar (Table 12), whereas those taken 1 day apart at the beginning of the 9 days were only 89 to 92% similar. The increase in the observer's familiarity with the vegetation was a result of improved species identification and recollection of the characteristics of certain quadrats.

The main factors that influenced the precision of observations were plant morphology, distribution of individuals, and incorrect identification of species. These errors resulted in a total uncertainty in repetitive estimations of 10%. The greatest uncertainty in cover estimates was found in those species with small mean covers. Since errors have both relative and fixed components, those species whose uncertainties were dominated by fixed errors, caused my mis-identification or distribution, had very large percent errors at low covers. A similar increase in relative error at low cover

Table 12. Sorensen's similarity indices (%) for nine repetitive site samplings of a *Pinus contorta* stand in Alberta, Canada.

1								
91	2							
92	93	3						
91	92	96	4					
90	93	96	94	5				
90	92	93	93	96	6			
90	92	94	93	96	95	7		
89	92	93	92	96	96	96	8	
89	93	93	94	95	97	96	96	9

values has been shown for lichens (Addison 1984). Rounding errors also tend to increase the relative error in measurement at low-cover values.

When all species were considered, the similarity between sampling times did not improve with the elimination of the highly variable species. These highly variable species were normally those with the lowest covers and, since Sorenson's index weights each species by its cover, the influence of these species was minimized.

Seasonal variation in plant cover is an inherent aspect of the plant community and, therefore, it was not unexpected that cover estimations taken in the spring and autumn of the year differed from those taken in the summer. What was not expected, however, was the relatively long period of time in which cover changed very little (June to August; Table 13). This appears to be a result of the evergreen nature of the species (mosses) that dominate the cover of the lower stratum and, hence, the similarity index.

The total uncertainty in the visual estimation of plant cover in the *Pinus contorta* stand (Table 14) resulted from both measurement errors and between-year variation. Seasonal variation was minimized by sampling only in August. The total uncertainty was about 20%; 10% due to errors in sequential measurements and 10% due to between-year variation. It appears, therefore, that even if changes in plant cover between sampling times were statistically significant, they would have to exceed 20% before interpretation was possible. This systematic error in the estimation of plant cover may be a limiting factor in the utilization of plant community measurements for biomonitoring purposes.

Uncertainty in the estimation of plant cover did not, however, account for the changes in the vegetation at sites severely contaminated by elemental sulphur in this case. Shrub and herb cover and diversity decreased 98% and 76%, respectively. Decreases occurred over a 5-year period and, initially, were greater for herbs than they were for shrubs. The decline in the herbs occurred 1 year before decreases in half the shrub species (unpublished data, this laboratory). Mosses were the most sensitive species and had declined to about 1% cover from an estimated 50% cover after only 2 years of significant elemental sulphur dusting (Kennedy et al. 1985).

It is apparent, based on this study, that before a technique is used in biomonitoring, a full analysis must be carried out to determine both

Table 13. Sorensen's similarity indices (%) for the May to September 1983 site samplings of a *Pinus contorta* stand in Alberta, Canada.

May				
77	June			
77	92	July		
74	88	91	August	
79	81	80	86	September

Table 14. Sorensen's similarity indices (%) for the annual (August 1981 through 1984) site samplings of a *Pinus contorta* stand in Alberta, Canada.

1981			
80	1982		
79	87	1983	
75	89	84	1984

the precision of the technique itself and the feasibility of using the technique, given the natural variability in the system itself. In the case of plant communities, each community will be different, and our findings can only give some general guidelines for the level of uncertainty and the seasonal variation that must be addressed before community analysis can be used as a biomonitoring technique.

In this study, we used a lichen technique that had been tested for both its precision and its effectiveness to measure lichen response to air pollution in the Athabasca Oil Sands area (Addison 1984). Despite this earlier study that found arboreal lichens could be photographed and the cover determined for certain species groups, the technique did not appear effective in this area. It appears that a combination of the variability in lichen cover and inherent differences in the lichen habitat prevented the effective use of the technique, and no definitive statement on the effect of sour gas processing on lichen plant communities could be made. This shows clearly the importance of on-site testing of each biomonitoring technique used.

In 1981, a concerted attempt was made to determine whether the trees in the vicinity of sour gas processing had been affected by the operations. Ten trees (<10 cm DBH) were harvested at each site. Measurements were made of the height, diameter, and the length between terminal bud scale scars on the leader for the past 5 years. The top five branches (>5 years old) were collected, separated into age classes, and dried. Needle number and weight, and stem length and weight were recorded. In addition, basal disks were collected and the basal increment measured with a Digimicrometer. A sample of 2- to 5-year cones was taken from the 10 trees. The number of seeds per cone and the viability of the seed were determined.

No pattern in either tree growth or reproduction that could be attributed to pollution was seen. The natural variability in the stands of trees was substantial and the coefficient of variation for basal area growth at all sites, for example, was about 55% (Table 15). Using the ratio of tree growth, after the gas plant started up, to tree growth, prior to start-up, reduced the coefficient of variation, but the range of values in the sulphur-dusted sites was about 30%.

Table 15. Characteristics of *Pinus contorta* at the biomonitoring sites. Values are means ± 95% confidence limits.

Site	Age (y)	Height (m)	Growth Rate			Ratio of Basal Area 1972 to 1981/1962 to 1971	Reproduction	
			Leader ($cm \cdot yr^{-1}$)	Lateral Branches ($cm \cdot yr^{-1}$)	Basal Area (1972 to 1981) ($cm^2 \cdot yr^{-1}$)		Seed Production (seeds/cone)	Viability (% filled seed)
Sulphur-dusted								
1	49 ± 1	17.4 ± 1.2	27 ± 7	7.8 ± 0.7	85.8 ± 26.1	1.07 ± 0.26	22	86 ± 13
2	73 ± 4	20.3 ± 2.5	14 ± 5	5.3 ± 0.9	65.8 ± 37.7	0.97 ± 0.30	27	74 ± 15
5	75 ± 2	20.9 ± 1.2	14 ± 4	6.0 ± 0.6	64.8 ± 37.8	0.93 ± 0.31	29	86 ± 12
15	76 ± 2	20.3 ± 1.3	13 ± 3	5.3 ± 0.7	52.3 ± 22.8	1.29 ± 0.24	27	87 ± 12
Sulphur-gas exposed[a]								
3	104 ± 3	22.4 ± 1.4	6 ± 1	3.1 ± 0.2	43.6 ± 20.3	1.09 ± 0.37	37	87 ± 17
11	99 ± 3	24.5 ± 1.9	8 ± 2	4.2 ± 1.0	104.0 ± 44.4	1.06 ± 0.22	35	75 ± 15
12	95 ± 8	22.6 ± 1.3	5 ± 3	2.8 ± 0.4	40.2 ± 17.1	0.89 ± 0.30	15	83 ± 17
13	71 ± 5	21.6 ± 0.8	18 ± 5	6.8 ± 1.4	137.0 ± 56.6	0.93 ± 0.12	28	39 ± 31
14	78 ± 3	22.2 ± 1.4	11 ± 3	4.0 ± 0.6	66.0 ± 29.4	1.27 ± 0.35	39	75 ± 13
23	106 ± 2	17.8 ± 1.3	10 ± 2	4.3 ± 0.3	35.8 ± 16.1	0.94 ± 0.23	30	84 ± 10
All sites								
	89 ± 8	19.2 ± 1.2	11 ± 2	4.5 ± 0.6	60.5 ± 13.0	1.01 ± 0.08	29 ± 2	80 ± 5

[a] The sulphur gas designation refers to sites that have 7-year mean sulphation rates >0.05 $mg \cdot dm^{-2} \cdot d^{-1}$ (SO_3).

5. SUMMARY

In order to adequately design a monitoring program, the objective of the study must first be defined. For example, it makes no sense, economically or otherwise, to design an elaborate soil-sampling program to provide an estimate of total S in the LFH horizon, with a high degree of precision, when the object of the program is to provide an estimate for liming. Conversely, compositing of samples may reduce the variability of the total S measurement (which is what is needed for determining the lime requirement) but prevents quantitative comparisons from one time to the next, or from one site to another.

Defining the objects of a monitoring study is only the first step in the preparation of a sampling program. A complete assessment has to be carried out to determine not only the variability of the technique, but also to determine if a given technique or measurement is feasible, given the variability. The use of the lichen technique described above is a good example. While the lichen response provided an excellent technique for use in the Fort McMurray area, the same technique provided no definitive information on the effect of sour gas processing on lichen plant communities in the Rocky Mountain House area.

When designing a long-term monitoring program to compare various parameters over time, the degree of confidence and level of significance required, plus an estimate of the resources available, must be considered. By partitioning the variability, as demonstrated above for several soil measurements, the optimum number of plots and number of replicates per plot to best estimate a given soil variable can be determined. It is important that the best possible estimate for the parameter(s) of greatest importance is determined, while sacrificing precision of the more variable but less important measurements. Again, this emphasizes the importance of testing techniques in an area prior to implementing a full-scale program.

The results of the 5-year study around the two sour gas processing plants of west-central Alberta demonstrated that S^0 had adversely affected both the soils and vegetation in the areas immediately adjacent to the plants (<500 m). Current deposition rates of S^0, however, are considerably lower than the rates that must have occurred to produce the concentrations of S^0 presently in the LFH horizon. From the direct measure of S^0 in the LFH horizon and by the use of lead candle data, areas of low-level S^0 or SO_2 deposition distant from the sour gas plants have been determined. Monitoring of the total S concentration in the LFH did not provide a very sensitive measure of S^0 deposition in the area because of the natural soil variability. In addition, because of the buffering capacity in the LFH and the low rate of deposition outside the areas of heavy S^0 impingement, no significant changes in pH could be detected. Other soil parameters measured and the various vegetation techniques used also showed no detectable effects outside the heavily contaminated areas. Therefore, outside of the area of heaviest S^0 impingement (>5000 mg•kg^{-1}), no detectable changes in the soils or vegetation measurements taken could be seen.

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AIR POLLUTION MEASUREMENTS AND EFFECTS RESEARCH:

A PERSPECTIVE ON AQUATIC DAMAGE

by

T.G. Brydges[1]

ABSTRACT

Canada has been the home of large mining and smelting industries for many decades. There are many examples of damage to the local environment caused by sulphur dioxide emissions from these companies. One of the earliest examples of sulphur dioxide damage crossing international boundaries was the Trail, British Columbia smelter case in the 1930s. Sulphur dioxide emissions were reduced at the Canadian smelter to protect the environment on the United States side of the border.

Studies of environmental damage from acidification by acid deposition in Canada date from the 1950s and 60s. In the late 1960s, acidification of surface waters and other forms of environmental damage, near point source emissions in Canada and the United States, led to development of Clean Air Acts in both countries and the implementation of various control programs. In North America, sulphur dioxide emissions reached all-time highs around 1970 and 1973 and then decreased from 28 x 10^6 t to 21 x 10^6 t from 1973 to 1984, and Canadian emissions decreased from 6.6 to 3.8 x 10^6 t in the same time period. United States emissions are projected to either stay the same or to rise slightly over the next decade unless further controls are taken. Canadian emissions are ensured to decrease as a result of the Eastern Canadian provinces agreeing to a 50% reduction in the 1980 emissions by 1994.

The aquatic environment has responded favourably to these emission reductions. Sulphate runoff in 12 Nova Scotian and 8 Newfoundland watersheds decreased by nearly 50% in the corresponding time. Rivers in both cases showed an expected increase in pH. Near Sudbury, Ontario, following reductions in emissions from the major smelters during the 1970s, surface water sulphate concentrations have declined, and the pH of the acidified lakes has increased with the hydrogen ion concentration decreasing by up to 65%.

The past reductions in sulphur dioxide and favourable response in the environment is most encouraging, but we are still faced with a situation of extensive surface water damage in Eastern Canada as shown by the ratio of lake alkalinity to calcium plus magnesium concentrations. Large areas of Eastern Canada have less than 20% of the alkalinity which would be expected from normal weathering processes, and as many as 14 000 individual lakes have been acidified. There are examples of the top metre of groundwater being acidified by a combination of sulphate and nitrate.

(Continued...)

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[1] Advisor, LRTAP Liaison Office, Atmospheric Environment Service, Environment Canada, Downsview, ON

Biological surveys have documented a continuing decline in biological quality of lakes and have documented the loss of aquatic organisms as a result of periodic pH depressions in streams. Therefore, we can conclude from the Eastern North American experience that, while emissions and deposition have been reduced and water quality has improved, the situation is still far from acceptable.

The question of what deposition must be reached in order to protect all surface waters is still a matter of research and discussion. The present objective for Eastern North America is to reduce deposition in all sensitive areas to no more than 20 kg of sulphate in wet deposition per year. It is recognized that some surface waters with very low alkalinity would still be acidified at this deposition value. In Western Canada, deposition values in sensitive areas are currently well below this value, and the environmental goal is to derive target values which will prevent acidification damage from occurring.

1. INTRODUCTION

Canada has been the home of large mining and smelting industries for many decades. There are many examples of damage to the local environment caused by sulphur dioxide (SO_2) emissions from these industries.

Non-ferrous smelters have been operating near Sudbury, Ontario for nearly a century. The environmental damage and poor local air quality became the basis of emission control programs, mostly designed in the 1960s and implemented in the 1970s. Inco Ltd., the largest company in the area, began reducing emissions in the early 1970s and also brought the world's tallest chimney (381 m) into use in 1972. The tall stack was designed to increase dispersion and thus improve local air quality, an action which was repeated by many companies outside of Canada during the 1970s. Falconbridge Ltd. also responded to a series of control orders and the company ultimately reduced SO_2 emissions by about 75% from the highest values of the 1960s. An extensive scientific project was instituted in 1972 with the goal of evaluating the local environmental quality resulting from the control actions and of determining the need for further control measures.

Canadians have also become familiar with airborne pollution as a trans-boundary problem. In the 1930s, SO_2 emitted from a smelter in Trail, British Columbia was shown to be causing damage on the American side of the border. Canada and the United States opened negotiations on the problems which resulted in the Canadian Government ordering control actions.

While there are international aspects of the Trail case, the problems were generally regarded as local in nature. However, in 1972, Sweden drew attention to acidification being caused by the long-range transport of pollutants and, in the mid 1970's Canadian studies progressed from dealing with the local problems in the Sudbury area to the widespread acidification of surface waters in Eastern Canada. While the problem is far from solved in North America, we have made some encouraging progress.

2. CHANGES IN SO_2 EMISSIONS

In North America, SO_2 emissions reached all-time highs between 1970 and 1973. As a result of both Canada and the United States instituting Clean Air Acts and enforcing more stringent standards for local air quality, a large amount of SO_2 was removed from the stack gases. Large increases in energy costs also encouraged energy conservation and reduced fuel consumption during this period.

Figure 1 shows the trends of SO_2 emissions in the United States from 1900 to 1983 (Environmental Protection Agency 1985, 1986). There has been a decline of about 30% from 1973 to 1983. This decline is attributed to: (1) stringent new source performance standards; (2) lower sulphur content of the coal consumed; and (3) retrofitting of scrubbers (National Coal Association 1986), among other things.

Projections for the next decade for United States utilities vary from a continuing decline predicted by the National Coal Association (1986), to increases of as much as 5×10^6 tons, unless further control measures are introduced (ICF Incorporated 1986).

In Eastern Canada, SO_2 emissions declined by about 50% during the 1970s and early 1980s (Figure 2). Although this decline can be attributed partly to reduced economic activity in the last few years, it has been largely due to SO_2 emission controls to improve air quality near the large non-ferrous smelters in Sudbury. In addition, one of the smelters at Sudbury, Inco Ltd., and the thermal power plants of Ontario Hydro are now operating under special regulations introduced to control the long-range transport of SO_2. These regulations are over and above the controls needed to improve local air quality.

In Western Canada, SO_2 emissions have also declined from the early 1970 values (Table 1).

A further reduction in Canadian emissions has been assured by the federal/provincial agreements in Canada calling for a 50% reduction in Eastern Canadian SO_2 emissions by 1994. Both Canada and the United States still have a long way to go in technology development and technology implementation to achieve the required reductions by the mid-1990s, but we are confident that we will achieve our objectives of reducing deposition to acceptable values.

3. SURFACE WATER CHANGES IN CANADA

The declines in SO_2 emissions have caused a corresponding decrease in deposition in Eastern North America. Table 2 shows changes in the sulphate yields from watersheds in Nova Scotia and Newfoundland (Thompson in

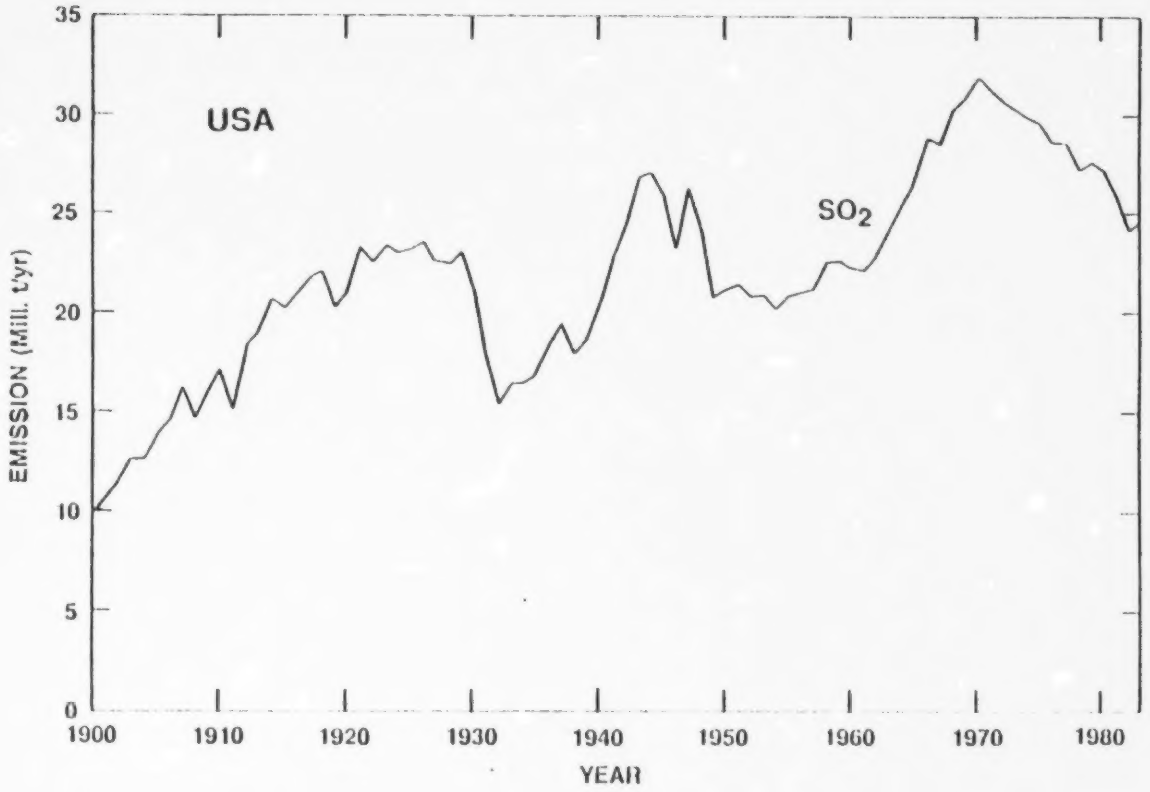

Figure 1. Sulphur dioxide emissions in the United States from 1900 to 1983.

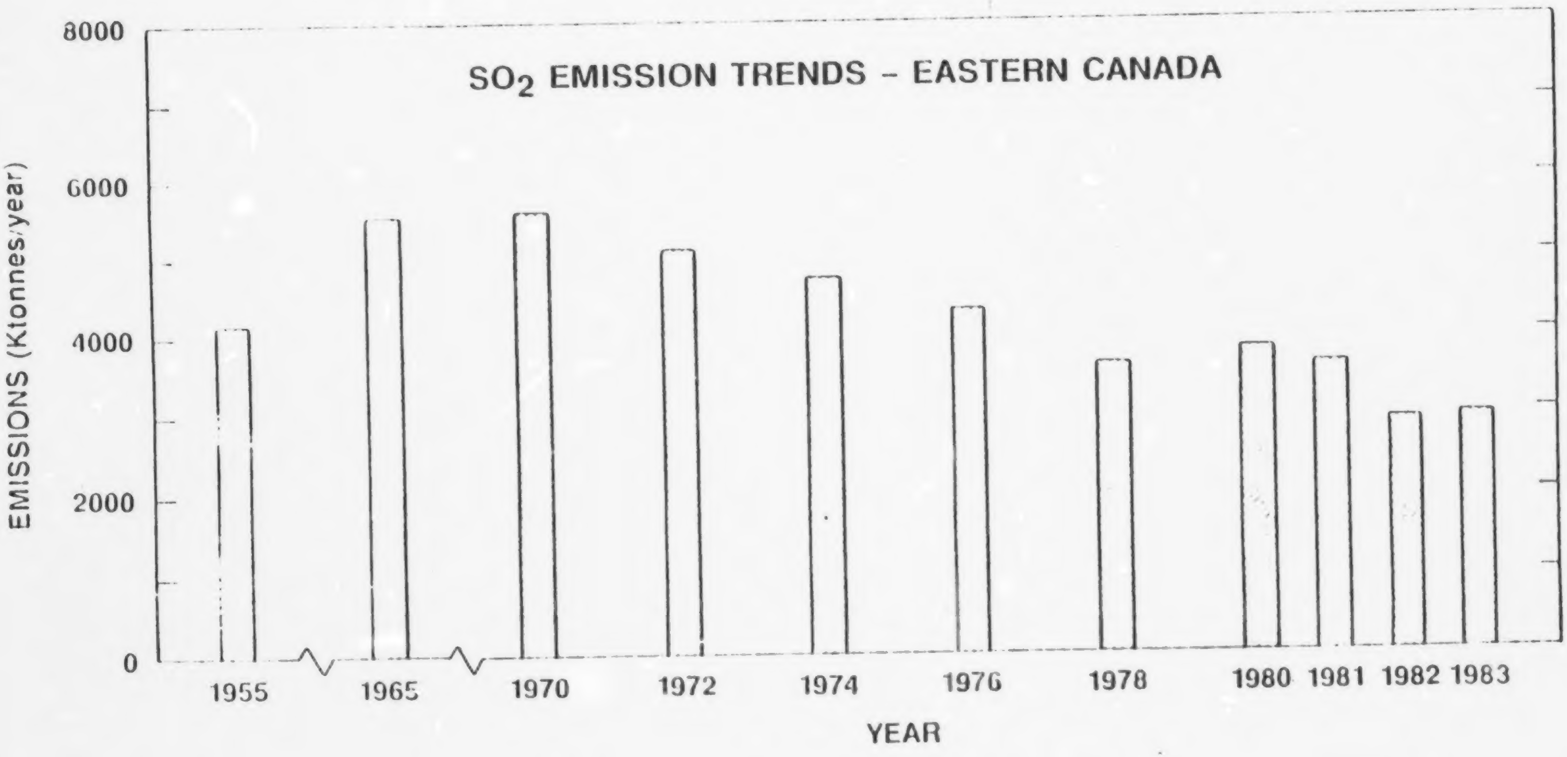

Figure 2. Sulphur dioxide emissions in Canada from 1955 to 1983.

Table 1. Sulphur dioxide emissions in Western Canada in kilotonnes.

	1970	1972	1974	1976	1978	1980	1981	1982	1983
British Columbia	359	428	404	371	260	167	164	139	150
Alberta	623	757	656	536	551	599	602	526	545
Saskatchewan	56	52	55	53	63	54	55	82	94
Totals	1038	1237	1115	960	874	820	821	747	789

Table 2. Sulphur dioxide emission changes; sulphate export from Nova Scotian (12) and Newfoundland (8) watersheds; and pH ranges from associated rivers.

	1971 to 1973	1982 to 1983	Change
SO_2 Emission in Eastern Canada and the United States (yearly averages in million tonnes/year)	27.0	20.3	-25%
Watershed Export ($kg \cdot ha^{-1} \cdot yr^{-1}$ SO_4)			
A Nova Scotia	39 + 6.7	21 + 6.1	-47%
B Newfoundland	32 + 12	18 + 8	-44%
pH Range of River[a]			
A Nova Scotia	4.4 to 6.5	4.5 to 6.7	
B Newfoundland	5.5 to 7.7	6.1 to 7.8	

[a] All rivers decreased in sulphate yield and increased in pH.

press). From the early 1970s to the early 1980s, the sulphate export from the watersheds measured in the runoff declined by nearly 50%, reflecting the decline in emissions in the areas upwind of the region. Atmospheric models have calculated an expected deposition reduction of 20 to 25%. These numbers are in good agreement, considering the expected error in model calculations and in the measurements, and are most encouraging with regard to demonstrating that a reduction in SO_2 emissions leads to reduction in sulphate in surface waters. Table 2 also shows the change in the pH of the rivers in the same time frame, and indeed, there has been the expected decline in acidity. The water quality is not yet acceptable for a healthy biological community, but there have been improvements.

Water quality has also improved in lakes in the Sudbury area following the major SO_2 emission reductions by the two largest smelters, Inco Ltd. and Falconbridge Ltd. (70 and 75% reductions, respectively) during the 1970s. By 1985, there had been about a 40% reduction in sulphate concentration in one study lake (Figure 3) (Dillon et al. in press), and a corresponding increase in pH from 4.1 to 4.6 (69% decrease in hydrogen ion). Substantial increases in pH were observed for a large number of acidified lakes being monitored in that area in an extensive survey (Figure 4) (Keller and Pitblado 1985). Biological recovery has been observed in two study lakes which have shown increased biomass of algae and increased diversity of both algae and zooplankton (Havas 1986, Pers. Comm., Institute for Environmental Studies, University of Toronto, Toronto, ON).

Our modelling calculations predict that other areas in Eastern North America have probably experienced some improvement in surface water quality as a result of the emission reductions. However, the result from our Nova Scotia and Newfoundland rivers, along with Sudbury results, fully substantiate the position that Canada has taken; i.e., reducing SO_2 emissions will lead to decline in acidity of surface waters.

The recent U.S. National Academy of Science (1986) report on trends indicates decreasing concentrations of sulphate in rivers in the northeastern United States and increasing concentrations of alkalinity. These findings are a further confirmation of the changes that are observed in the Atlantic Provinces of Canada.

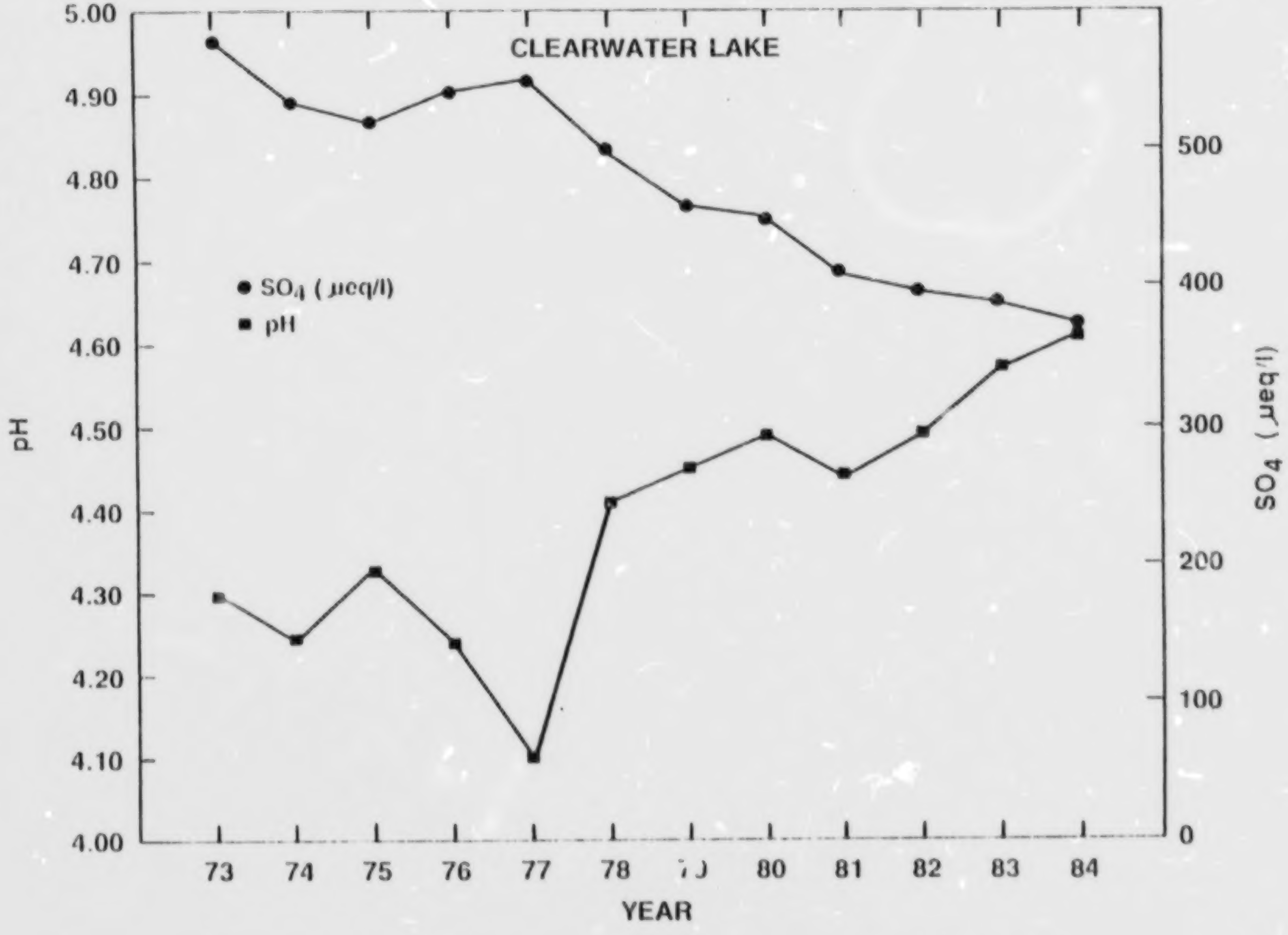

Figure 3. Trends in sulphate and pH values for Clearwater Lake, Ontario.

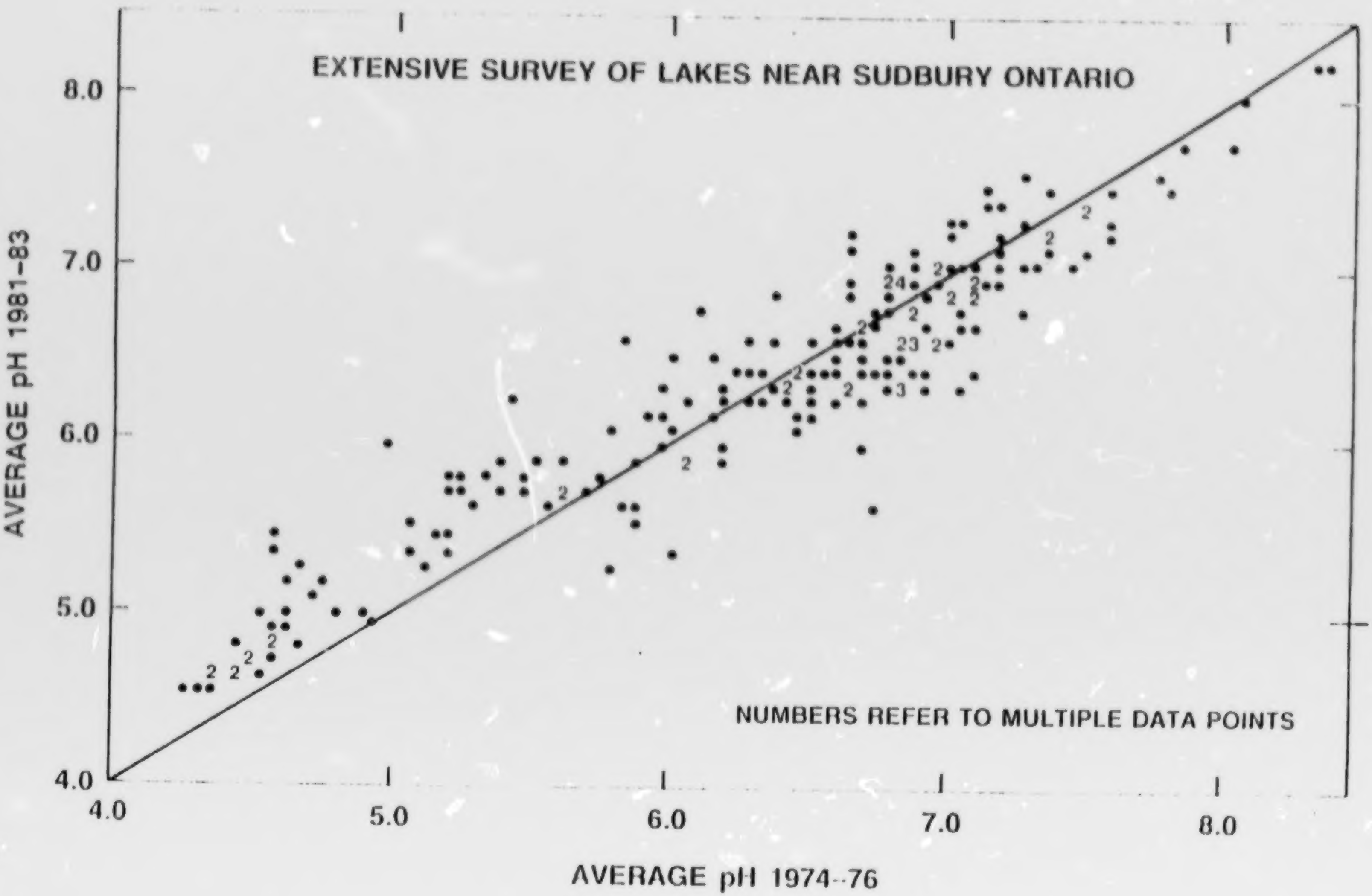

Figure 4. Changes in the distribution of average pH of lakes in the Sudbury area between the periods 1974 to 1976 and 1981 to 1983.

4. CURRENT STATUS OF SURFACE WATERS IN EASTERN CANADA

4.1 CHEMISTRY

While the obvious successes of past SO_2 reduction programs are encouraging, we must be aware of the fact that the present sulphate deposition is too high and present water quality is not acceptable.

Figure 5 (Jeffries 1986) shows the status of surface waters as measured by the ratio of alkalinity to calcium plus magnesium. There are many mechanisms used to explain the surface water acidification problem but, regardless of which mechanisms are causing acidification to occur, the ratio of alkalinity to calcium plus magnesium has been reduced, either by decreases in alkalinity, increases in calcium and magnesium, or both. Under normal weathering processes, the ratio will be unity. If the ratio becomes zero, then alkalinity has been exhausted and we regard the lake to have been acidified. Acidified lakes are devoid of fish and have reached an end-point with regard to biological damage. However, lakes which still retain some alkalinity nevertheless suffer biological damage. The map is based on about 8000 sample points.

Large areas of Ontario and Quebec fall within the 0.2 contour for the ratio. This means that the surface waters have less than 20% of the alkalinity which we would expect from normal weathering processes. Surface waters in Nova Scotia have been severely affected with a ratio of zero being common, and much of Newfoundland has also been damaged.

Within the most affected areas, some waters have been acidified. Our latest projection is that as many as 14 000 lakes have been acidified. It is our goal to see these ratios increase and eventually arrive back at the natural value of close to unity.

The cause of the low alkalinity values can be seen in Figure 6. The values of the ratio of sulphate to calcium plus magnesium mirrors the alkalinity ratios in Figure 5. As the alkalinity declines, it is replaced by sulphate. The areas of lowest alkalinity to calcium plus magnesium ratios are also the areas of highest sulphate deposition.

New findings on groundwater quality are of considerable concern to us. At one of our study sites near Sault Ste. Marie, Ontario, soil waters, down to about 1 m, have been acidified with a complete loss of alkalinity at

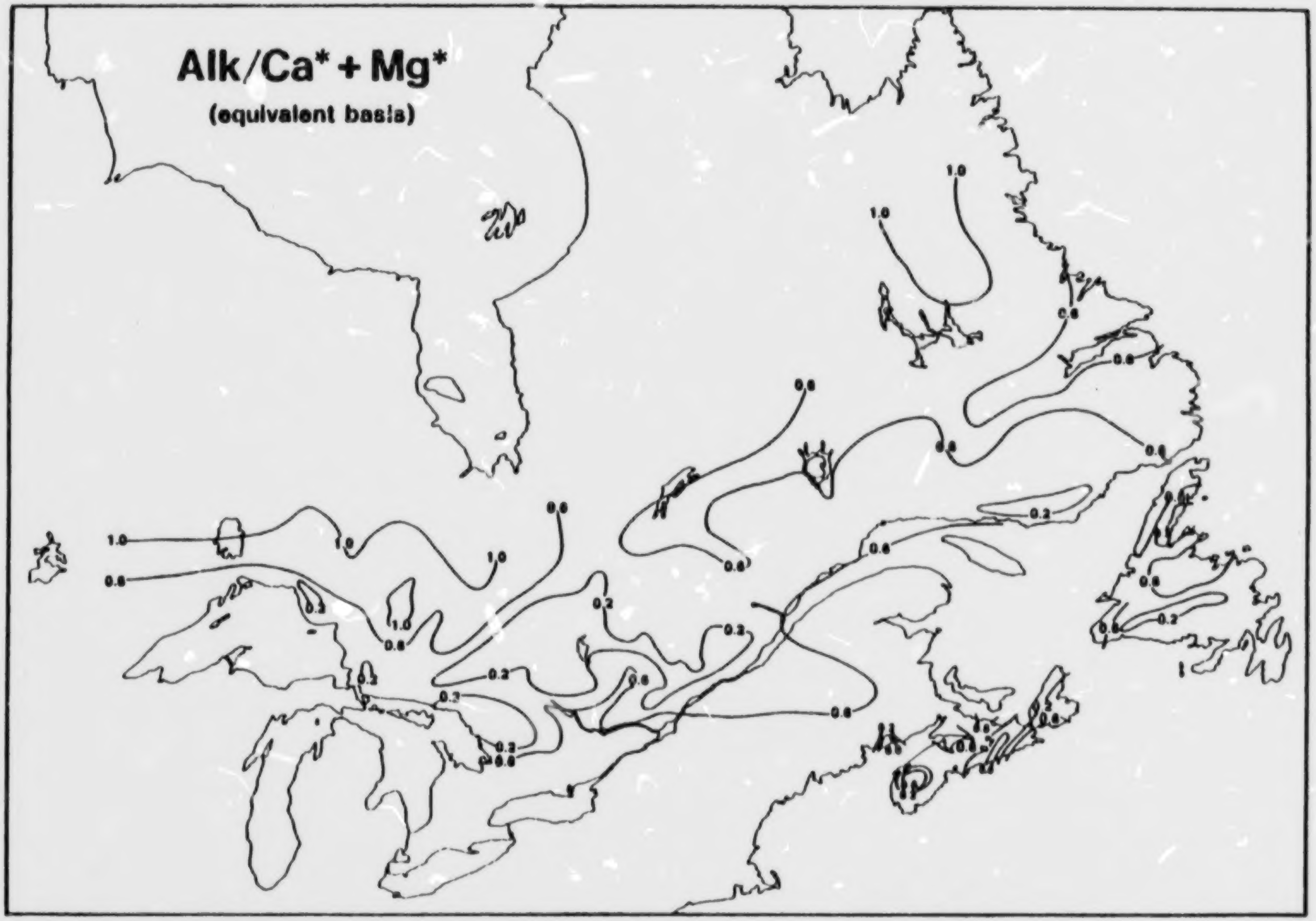
Alk/Ca* + Mg*
(equivalent basis)
1.0
0.6
0.2

Figure 5. The status of surface waters in Eastern Canada as measured by the ratio of alkalinity to calcium plus magnesium. This map is based on approximately 8000 sample points.

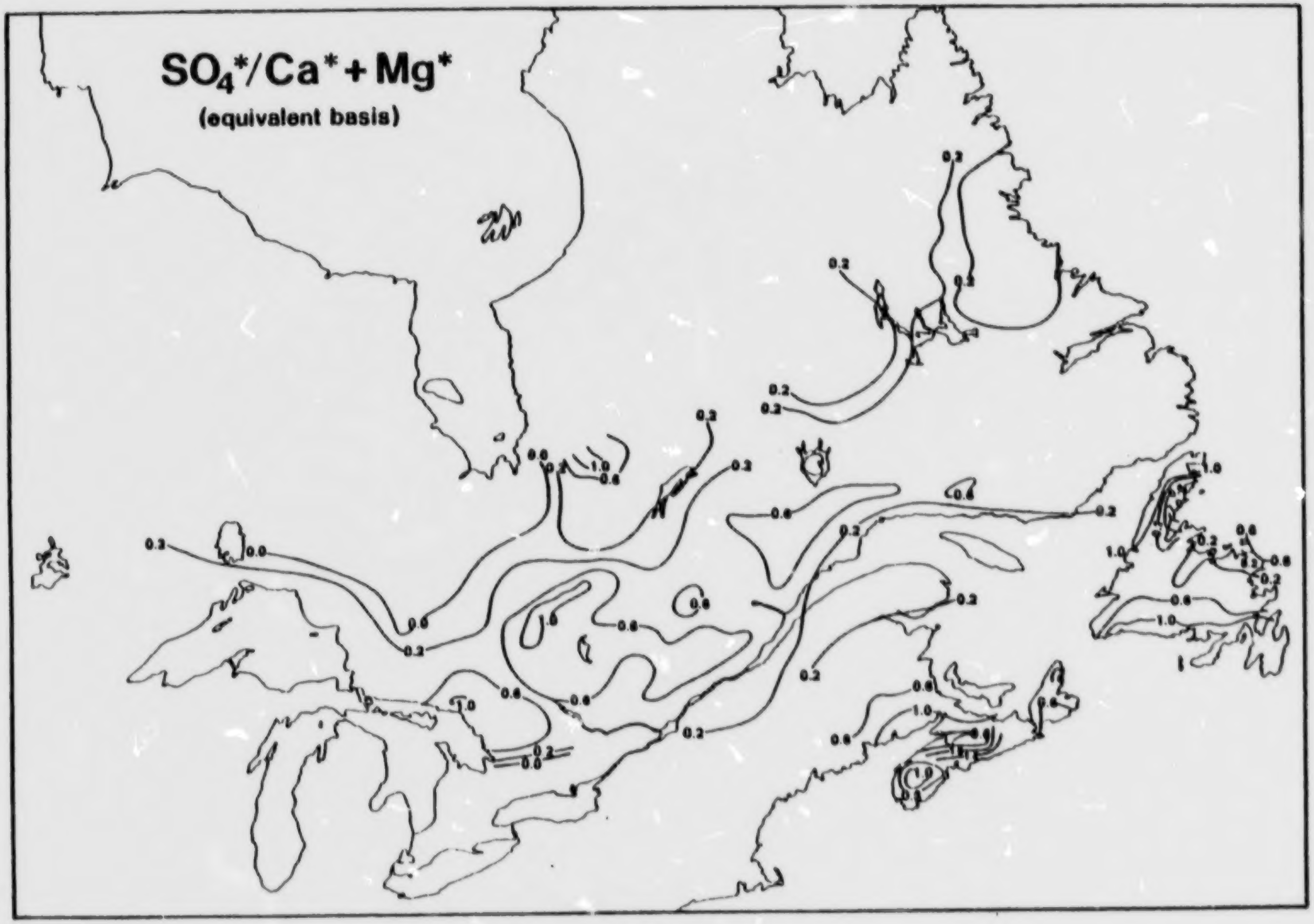
$SO_4^*/Ca^* + Mg^*$
(equivalent basis)
0.2
0.6
0.8
1.0
0.0

Figure 6. Estimates for the ratio of sulphate to calcium plus magnesium for the same lakes documented in Figure 5.

times. The lost alkalinity has been largely replaced by sulphate. During the most extreme conditions, nitrate contributes to the alkalinity loss as well. The depth of acid groundwater extends to below the depth of the root zone of the forest cover. Figure 7 shows the chemical composition of the water during periods of heavy rain and spring runoff when the groundwater becomes fully acidified (Johnston 1986, Pers. Comm., National Hydrology Research Institute, Saskatoon, Saskatchewan). In March, the groundwater was influenced by a heavy spring rain with low pH. Subsequently, alkalinity recovered slightly until the onset of spring melt in mid-April, when the alkalinity again fell to zero.

4.2 BIOLOGY

The current water chemistry in many of our lakes is detrimental to biological life even though some alkalinity remains. Rooke and Mackie (1984) have recorded the recent collapse of a mollusc species in a lake under study in Central Canada. This is an important observation because it confirms that the biological quality of the lake is deteriorating with time. Another recent report of biological damage is based on extensive baseline data collected over 40 years ago in Algonquin Provincial Park in Ontario. Acid-sensitive species of stream invertebrates have been eliminated. This has been caused by repeated short-term pH depressions in the stream rather than by long-term acidification (Hall 1986, Pers. Comm., Ontario Ministry of the Environment, Dorset, Ontario). This important observation demonstrates the loss of biological quality under chemical stress conditions.

5. EFFECT OF ORGANIC ACIDS ON ACIDIFICATION

Organic acids have often been proposed as the cause of surface water acidification rather than atmospheric deposition. This theory can be rejected on the basis of many studies. As indicated in Figures 5 and 6, sulphate replaces bicarbonate in surface waters in the areas of high atmospheric sulphate deposition.

Johnson (1985) analyzed runoff water from 19 rivers in the Georgian Bay area and found that organic acids averaged only about 15% of the anions. Data from 27 lakes and streams in Pukaskwa National Park (Sutton et al. 1983) indicated that organic acids could account for up to 30% of the anions but

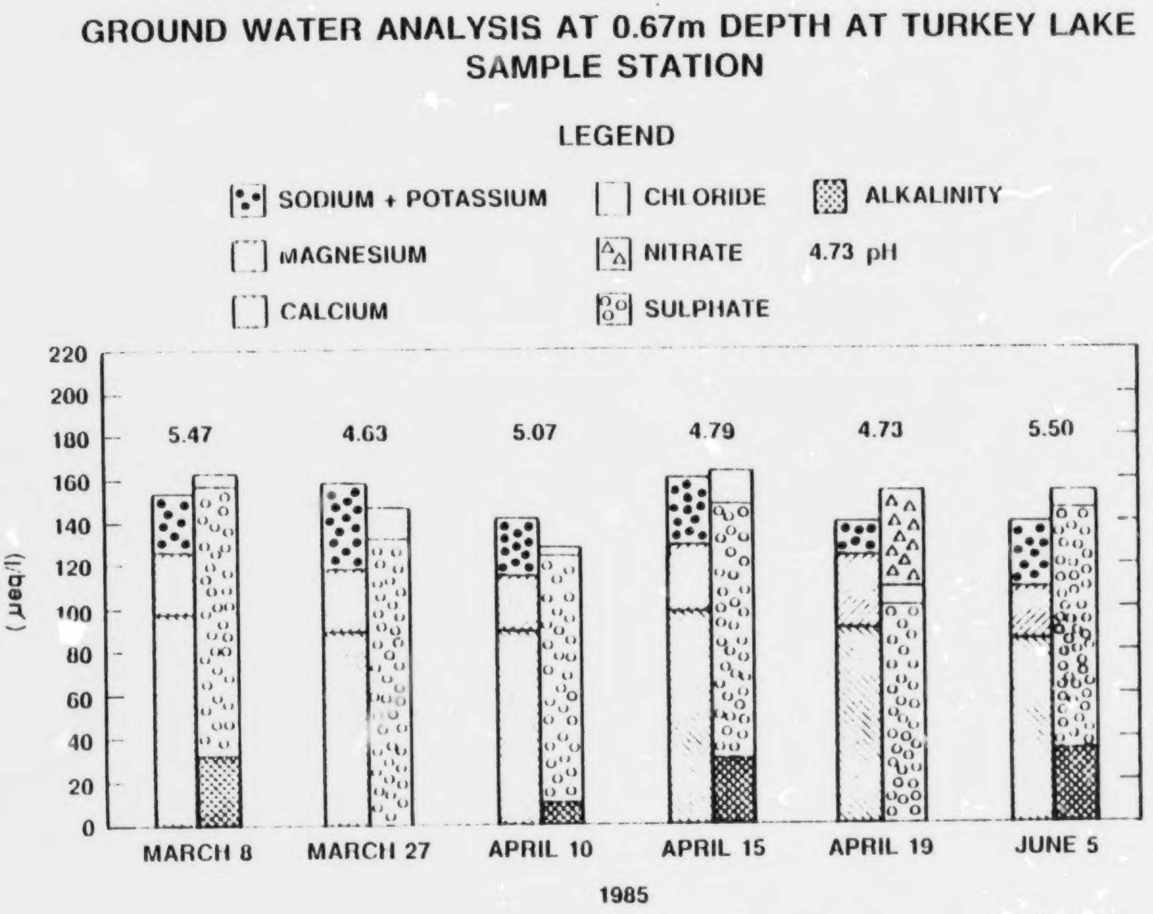

Figure 7. The chemical composition of soil water during periods of heavy rain (March) and spring runoff (mid-April) for a watershed near Sault Ste. Marie, Ontario.

generally less than 20%. LaZerte and Dillon (1984) tested the theory of organic acids causing the observed acidification and rejected the theory based on field data. Organic acids were not important during periods of high flow or on an annual basis.

The recovery of surface water pH values following SO_2 reductions further demonstrates that the so-called 'alternate theories' of acidification do not apply in Eastern Canada.

6. TARGET LOADING

In 1980, Canada and the United States signed a Memorandum of Intent (MOI) indicating the two countries' determination to develop a bilateral acid rain control agreement. Committees were established to develop the required support documents. The aquatic effects subgroup was charged with the task of estimating deposition values which would protect surface waters.

Observations of aquatic effects were assembled for five study areas in the United States and six areas in Canada, stretching from Saskatchewan to Nova Scotia. Surface waters receiving more than 20 $kg \cdot ha^{-1} \cdot yr^{-1}$, based on 1980 data, were observed to be damaged by acidification; those receiving less than about 10 $kg \cdot ha^{-1} \cdot yr^{-1}$ were not damaged. There were limited data available in the 10 to 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ deposition range. However, it was concluded from the field observations and supported by theoretical considerations that, for a maximum deposition of 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ of sulphate in wet deposition, nearly all surface waters would be protected from acidification damage. The data did suggest that extremely sensitive surface waters (very soft waters) would still experience some acidification damage. The deposition data are summarized in Figure 8.

The areas of highest sulphate deposition correspond to the areas of lowest alkalinity to calcium plus magnesium ratios in Figure 5 and the highest values of the sulphate to calcium plus magnesium ratios in Figure 6.

It is very important to realize that the goal is to have all sensitive areas in Eastern North America at a maximum of 20 $kg \cdot ha^{-1} \cdot yr^{-1}$. Canadian and United States SO_2 control programs, which are sufficient to achieve this goal in the Adirondacks, will in fact result in deposition in all of the sensitive areas of Canada being less than 20 $kg \cdot ha^{-1} \cdot yr^{-1}$. Atmospheric model calculations predict that the current Canadian control

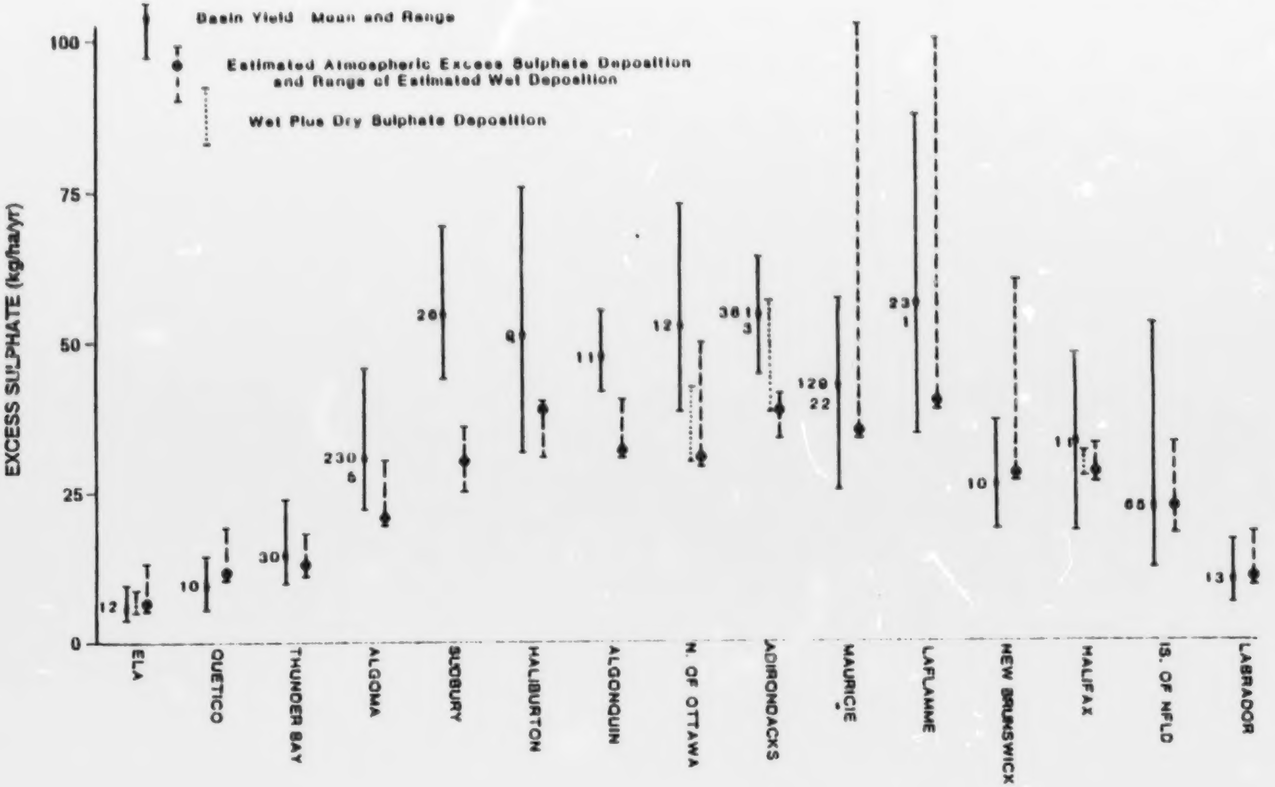

Figure 8. Modified from Figure 3-16, United States-Canada Memorandum of Intent Work Group 1 Report (1983).

Mean and range of basin specific yield of excess sulphate (*) compared with estimated atmospheric excess sulphate deposition (·) in precipitation for 1980 (Thompson and Hutton 1982) and the range of estimated wet deposition for 1977-1980 from the CANSAP precipitation network (Barrie and Sirois 1982). Also shown are wet plus dry deposition of sulphate calculated from 1980 measurements of SO_x in air at four APN stations (Barrie 1982). The Maniwaki wet deposition data have been combined with the Chalk River dry deposition data for purposes of comparison.

objective of 2.3 x 10^6 t of SO_2, plus a 50% reduction in the United States, would result in maximum deposition in the Muskoka and Quebec City areas in the range of 13 to 23 $kg \cdot ha^{-1} \cdot yr^{-1}$. Other Precambrian areas would have lower deposition and hence be protected to a greater extent.

The 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ target is unique to Eastern North America. Since it is heavily based on direct observations, it takes into account the particular soils and rock conditions, climate, wet and dry deposition ratios, and weather patterns. The target cannot be expected to apply to other areas (without testing), nor could target loadings developed in other places necessarily apply to Eastern North America.

In Western Canada, a more appropriate objective for target loading values is to prevent surface water damage as lakes are currently not experiencing acidification effects. It is not proposed that deposition in all sensitive areas be allowed to increase to 20 $kg \cdot ha^{-1} \cdot yr^{-1}$, and it can be expected that a lower deposition would be needed to prevent any surface water damage in presently unaffected surface waters. Deposition in the range of 11 to 15 $kg \cdot ha^{-1} \cdot yr^{-1}$ may be needed to prevent any damage in even the most sensitive surface waters.

Several studies are under way to evaluate target loadings, with the aim of establishing 'non-degradation' values for western and central areas of North America.

In areas of very high rainfall, such as British Columbia, the acid sulphate deposition concept may have to be modified. High deposition values can result from relatively low rainfall concentrations. In such cases, it will be necessary to frame the target loadings in terms of concentrations. This emphasizes the fact that target loadings can be very specific to regional conditions.

Soils in Western Canada contain large amounts of sulphate. Wind-blown dust can thus contribute large amounts of sulphate to the rainfall in the form of neutral calcium sulphate. Therefore, sulphate may not be a good surrogate for the acidifying effect of the rainfall in Western Canada.

7. CONCLUSIONS

We have observed reduced acidification of surface waters as a result of SO_2 emission reductions. Chemical and biological quality of surface waters have improved in study lakes.

However, in heavily affected areas, the current deposition of sulphate is too high and the biological quality of some surface waters is still deteriorating.

Surface waters in extensive areas of Eastern Canada are badly damaged, with alkalinity values of less than 20% of the expected natural value. Sulphate has been shown as the cause of the lost alkalinity.

Acidification of groundwater by acid deposition has been found, and both sulphate and nitrate contribute to this acidification.

A target loading of 20 $kg \cdot ha^{-1} yr^{-1}$ of sulphate in wet deposition has been set for Eastern Canada. It is recognized that, in sensitive areas receiving this loading, some surface water damage will still occur. However, the goal is to reduce SO_2 emissions so that the maximum deposition in any sensitive area is 20 $kg \cdot ha^{-1} \cdot yr^{-1}$. Once this goal is reached for the Adirondack area or for the Muskoka-Haliburton area of Ontario, other sensitive areas will receive less than 20 $kg \cdot ha^{-1} \cdot yr^{-1}$ and, hence, be protected to a greater extent.

Target loading values for Western Canada must take account of both the amount of rainfall, which is highly variable, and the amount of sulphate from windblown dust.

The scientific basis for Canada's sulphur dioxide control policies has been fully supported by field observations.

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AN ASSESSMENT OF THE POTENTIAL SENSITIVITY OF ALBERTA LAKES TO ACID DEPOSITION

by

P.K. Erickson[1] and D.O. Trew[2]

ABSTRACT

Historical chemical data for 875 lakes throughout Alberta were assembled from provincial and federal data bases. In addition, a preliminary water quality field program, conducted in the fall of 1983, in the northern half of the province, provided data on a further 107 lakes. The chemical variables selected as criteria to identify potentially sensitive lakes were based on previous Canadian studies. These variables were pH, calcium, and alkalinity.

Values of pH ranged from 3.4 to 10.6, with 17% of the total sample of Alberta lakes having a pH of less than 7.0, indicating a moderate to high sensitivity to acid deposition. Calcium values ranged from 0.1 to 610.0 $mg \cdot L^{-1}$; 16.6% of the sample had values of less than 8.0 $mg \cdot L^{-1}$, indicating moderate to high sensitivity. Alkalinity values ranged from undetectable to 7772 $mg \cdot L^{-1}$; 9.7% of the sample had alkalinities of less than 20 $mg \cdot L^{-1}$, indicating moderate to high sensitivity.

Based upon these analyses, lakes in widely diverse areas of the province are potentially sensitive to the effects of acid deposition. A large number of these sensitive lakes is found on the Canadian Shield, in the extreme northeastern corner of the province. Several lakes in the Rocky Mountain national parks region, most notably Jasper National Park, are also sensitive. Most of the remaining potentially sensitive lakes are located in the northern upland regions, such as the Caribou and Birch Mountain uplands, and the Clear Hills and Swan Hills uplands. A number of these lakes were highly coloured, muskeg-type lakes, indicating a high natural acidity.

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[1] Environmental Protection Service, Environment Canada
[2] Water Quality Control Branch, Pollution Control Division, Alberta Environment

1. INTRODUCTION

Acid deposition is a serious environmental issue in Eastern Canada, Northeastern United States, and in Europe, where chemical and biological changes within aquatic ecosystems have been extensively documented (Dochinger and Seliga 1976; Leivestad et al. 1976; Watt et al. 1979; Drablos and Tollan 1980; National Research Council of Canada 1981). In Western Canada, where sulphate and nitrate emissions and deposition rates are lower, the issue has been less prominent until recently.

Total sulphur dioxide (SO_2) emissions in Canada in 1982 were 3 636 000 t (Canada 1986), of which the four western provinces collectively contributed over one-third, or 1 119 277 t (Table 1). Over 95% of SO_2 emissions in Manitoba originate from nickel, zinc, and copper production in the northern half of the province (Campbell 1984). In Saskatchewan, 60% of emissions are from power generation stations in the southern half of the province (Howard and Underwood 1984). Alberta is the major oil and gas producing province in Canada and 78% of SO_2 emissions are related to this industry (Alberta 1984). Natural gas processing, fuel combustion, and lead and zinc production are responsible for 70% of SO_2 emissions in British Columbia (Canada 1980).

In order to identify aquatic ecosystems potentially sensitive to acid deposition, the National Research Council of Canada (1981) has recommended that regional surveys of chemical, physical, and biological variables of aquatic systems be conducted. In accordance with this recommendation, the Technical Committee on Western Canada - Long Range Transport of Atmospheric Pollutants (LRTAP) instituted a co-ordinated program to map the sensitivity of surface waters to acid deposition. In Alberta, the assessment was conducted by the Water Quality Control Branch, Pollution Control Division, Alberta Environment.

The primary objective of this paper is to examine the potential sensitivity of Alberta lakes to acid deposition. The sensitivity of other Western Canadian lakes will be reviewed briefly as well.

2. METHODS

The collection of data occurred in two phases. Phase One included the compilation of existing water quality data for 875 Alberta lakes; for

Table 1. Canadian sulphur dioxide and nitrogen oxide (NO_x) emissions for 1982.

Province	Emissions (tonnes/year)	
	SO_2	NO_x
Alberta[a]	488 297	353 511
Saskatchewan[b]	97 496	127 423
Manitoba[c]	366 480	72 194
British Columbia[d]	107 004	198 373
Total	1 119 277	751 501
Total Canada[e]	3 636 000	1 872 000

[a] Alberta (in press).
[b] Howard and Underwood (1984).
[c] Campbell (1984).
[d] Canada (1980); B.C. data - 1980.
[e] Canada (1986).

complete data source references, see Erickson (1985). Only data collected during the open-water period of May 01 to October 31 of each year were included in the analysis.

Phase Two consisted of a preliminary lake sampling program undertaken to augment existing data or data derived from single samples, and to provide data for areas in the province which had not been sampled. One hundred and seven lakes were sampled between 1983 August 29 and 1983 October 26 from a float-equipped De Havilland Beaver aircraft. Profiles of physical variables were measured at the deepest part of each lake (determined through hydrographic maps). Dissolved oxygen and temperature values were obtained near the surface (0.25 m) and 1 m intervals down to the sediment. Surface (0.25 m) conductivity was measured. Transparency was determined by Secchi disc depth; the euphotic zone was estimated as 2.5 times Secchi disc depth. In situ pH was recorded at the surface (0.25 m) and 1 m above the sediment using a Metrohm E 588 meter. Field alkalinity was determined on the same day of sampling by potentiometric titration (American Public Health Association 1978); titrations were carried out with standardized sulphuric acid solution.

Depth-integrated samples were collected, using weighted Tygon tubing, from five widespread areas of each lake. Sample containers and Tygon tubing were triple rinsed with sample water. Samples were taken within the epilimnetic zone (in stratified lakes) or euphotic zone (in unstratified lakes). In shallow lakes (less than 2 m maximum depth) where the euphotic zone extended to the bottom, samples were collected to within 0.5 to 1.0 m of the sediment. Sample water was pooled, subsamples collected, and shipped by air to the laboratory within 2 days. Routine chemical analyses were conducted by the Alberta Environmental Centre at Vegreville.

3. MAPPING PROCEDURE

Upon completion of field work and compilation of historical data, all data were tabulated and summarized. In compliance with recommendations set forth by the Coordinating Committee on Surface Waters (Sawchyn 1982), alkalinity, calcium, and pH were selected as mapping criteria to ensure basic continuity with similar mapping projects completed in other parts of Canada

(Altschuller and McBean 1979; Liaw and Atton 1981; National Research Council of Canada 1981).

Following the criteria of Shewchuk (1981), alkalinity values were mapping according to the following intervals:

High sensitivity	0 to 10 mg.L^{-1}
Moderate sensitivity	11 to 20 mg.L^{-1}
Low sensitivity	21 to 40 mg.L^{-1}
Least sensitive	>40 mg.L^{-1}

For calcium, the National Research Council of Canada (1981) range was expanded to accommodate the geochemical heterogeneity found in Alberta and more intervals were created for values over 9 mg.L^{-1}:

High sensitivity	0 to 4 mg.L^{-1}
Moderate sensitivity	5 to 8 mg.L^{-1}
Moderate-low sensitivity	9 to 25 mg.L^{-1}
Low sensitivity	26 to 40 mg.L^{-1}
Least sensitive	>40 mg.L^{-1}

In order to combine small groups at the upper and lower end of the scale, the pH categories established by Liaw (1982) were reduced from 6 to 4, and the values were mapped according to the following intervals:

High sensitivity	> 6.5
Moderate sensitivity	6.6 to 7.0
Low sensitivity	7.1 to 7.5
Least sensitive	> 7.5

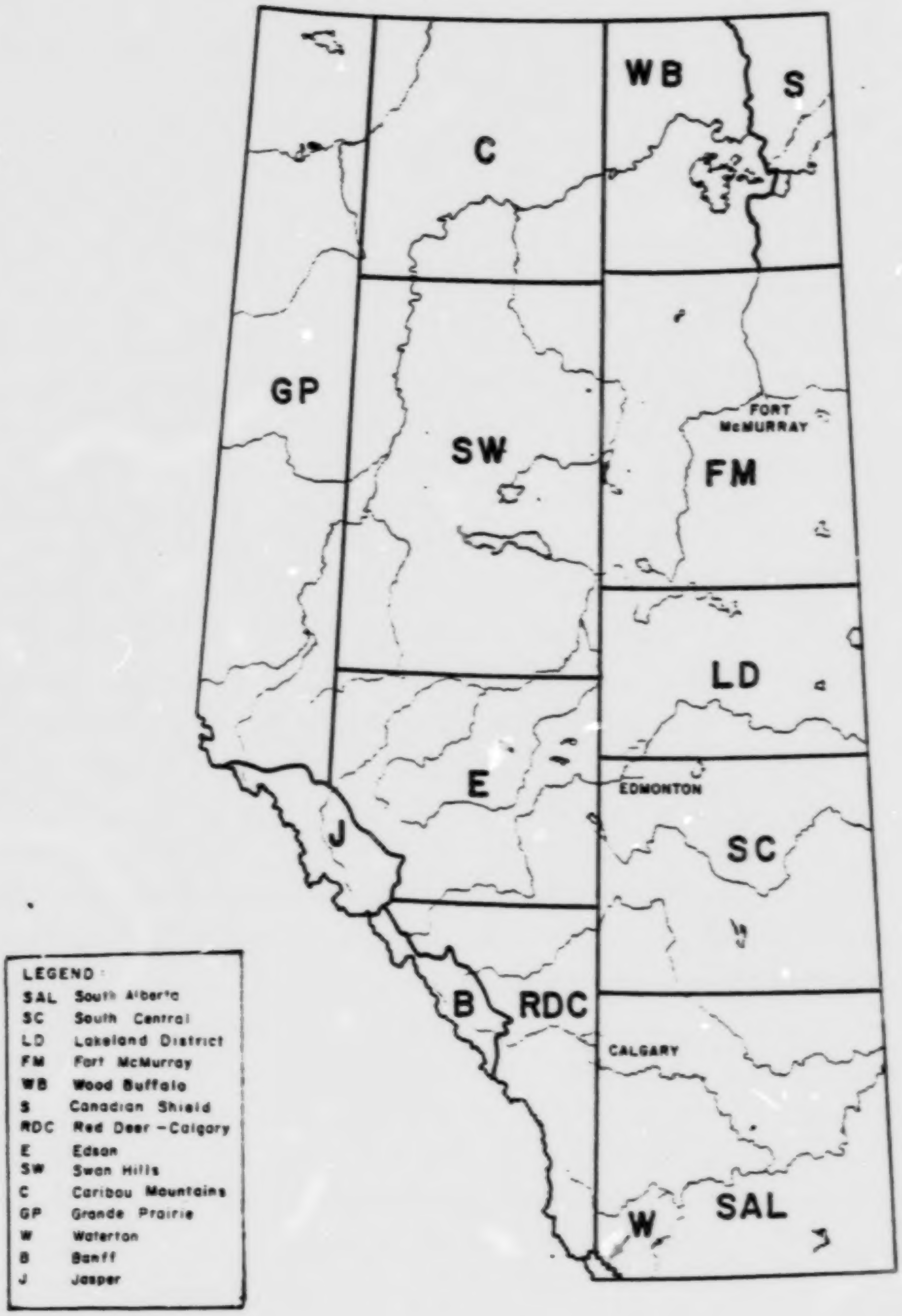
Where multiple values for a variable were available for a lake, means were calculated to obtain one point for mapping purposes. A network of Thiesson or Voroni polygons (Monmonier 1984), partitioning the region into proximal neighbourhoods around each control point (lake), was established to delineate boundaries of the sensitivity intervals.

4. RESULTS

In order to facilitate analysis and discussion of results, the province was divided into 14 geographic regions (Figure 1).

4.1 ALKALINITY

Means and ranges of alkalinity values are presented in Table 2. Values varied from below detection, in small muskeg-fed lakes in the Fort McMurray region, to 24 395 mg.L^{-1}, in a highly saline lake of southern


WB
S
C
GP
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FORT McMURRAY
FM
LD
E
EDMONTON
J
SC
B
RDC
CALGARY
W
SAL
LEGEND:
SAL South Alberta
SC South Central
LD Lakeland District
FM Fort McMurray
WB Wood Buffalo
S Canadian Shield
RDC Red Deer - Calgary
E Edson
SW Swan Hills
C Caribou Mountains
GP Grande Prairie
W Waterton
B Banff
J Jasper

Figure 1. Delineation of regions.

Table 2. Summary statistics of alkalinity values for Alberta regions.

Region	n	Mean ($mg \cdot L^{-1}$)	Range ($mg \cdot L^{-1}$)
South Alberta	70 (76)[a]	231	28 to 966
South-Central	54 (57)	1494	104 to 24 395
Lakeland	84 (84)	235	49 to 1 858
Fort McMurray	75 (75)	73	5 to 204
Wood Buffalo	90 (91)	125	LD[b] to 569
Canadian Shield	116(116)	34	2 to 99
Red Deer-Calgary	21 (35)	130	35 to 335
Edson	52 (52)	147	29 to 320
Swan Hills	87 (87)	88	LD to 382
Caribou Mountains	40 (40)	73	6 to 794
Grande Prairie	77 (78)	72	3 to 444
Jasper	101(101)	71	0.1 to 256
Banff	64 (64)	74	11 to 213
Waterton	26 (26)	245	11 to 7 772

[a] Number of lakes with alkalinity data (total number of lakes).
[b] LD = Less than Detection.

Alberta. In some regions, the mean values were skewed by very high alkalinity values found in a few of the lakes. For example, mean alkalinity for lakes in the Waterton region was 245 $mg \cdot L^{-1}$, although 77% of the lakes had mean values less than 40 $mg \cdot L^{-1}$.

Approximately 10% of Alberta lakes had alkalinity values less than 20 $mg \cdot L^{-1}$ (moderate to high sensitivity), and 90% had values greater than 21 $mg \cdot L^{-1}$. Seventy-five percent of lakes examined had alkalinity values greater than 40 $mg \cdot L^{-1}$, and 43% of the latter group had alkalinity values greater than 100 $mg \cdot L^{-1}$.

There was a significant north-south difference in the magnitude of mean alkalinity values. Higher proportions of lakes with high alkalinity values (>40 $mg \cdot L^{-1}$) were found in the southern regions (SAL, SC, LD, RD-C, and E on Figure 1). Lakes with low to moderate mean alkalinity values (<20 $mg \cdot L^{-1}$) were confined exclusively to the northern and national parks regions; within most of these regions, lakes with low alkalinity values (<10 $mg \cdot L^{-1}$) comprised less than 10% of the total lakes sampled.

4.2 CALCIUM

Means and ranges of calcium values are presented in Table 3. Values varied from 0.1 $mg \cdot L^{-1}$, in small muskeg-fed lakes in the Fort McMurray region and in Jasper National Park, to 810.0 $mg \cdot L^{-1}$, in the Wood Buffalo region. Calcium values in approximately 9.5% of lakes were less than 4 $mg \cdot L^{-1}$ (highly sensitive). Lakes with calcium values of 5 to 8 $mg \cdot L^{-1}$ (moderately sensitive) comprised 11% of the sample. Calcium values in 40% of lakes sampled varied from 9 to 25 $mg \cdot L^{-1}$, and 40% had calcium values greater than 25 $mg \cdot L^{-1}$. Within the latter group, 12% had calcium values greater than 40 $mg \cdot L^{-1}$.

There was a significant north-south alignment of calcium values; lakes with low values (<8 $mg \cdot L^{-1}$) were primarily confined to the northern and national parks regions. A preponderance of lakes with low calcium values characterized the Canadian Shield (65%), Caribou Hills (55%), and Waterton National Park (35%) regions.

Table 3. Summary statistics of calcium values for Alberta regions.

Region	n	Mean (mg·L^{-1})	Range (mg·L^{-1})
South Alberta	59 (76)[a]	33.0	6.0 to 102.6
South-Central	44 (57)	32.0	1.6 to 370.0
Lakeland	80 (84)	30.0	4.0 to 57.0
Fort McMurray	74 (75)	17.0	<1.0 to 37.7
Wood Buffalo	91 (91)	79.0	0.1 to 810.0
Canadian Shield	116(116)	8.0	0.7 to 27.7
Red Deer-Calgary	16 (35)	32.0	11.8 to 47.0
Edson	47 (52)	32.0	9.0 to 157.4
Swan Hills	87 (87)	28.0	1.9 to 121.0
Caribou Mountains	40 (40)	23.0	<1.0 to 296.0
Grande Prairie	76 (78)	23.0	<1.0 to 75.0
Jasper	101(101)	23.0	0.1 to 109.0
Banff	64 (64)	24.0	3.3 to 59.4
Waterton	26 (26)	16.0	2.7 to 65.0

[a] Number of lakes with calcium data (total number of lakes).

4.3 pH

Since, by definition, pH values cannot be averaged arithmetically, regional means were not calculated; modal classes were considered more meaningful as measures of central tendency. Modal classes and ranges of pH values are presented in Table 4. Values varied from 3.4, in a small muskeg-fed lake in the Fort McMurray region, to 10.6, in a highly alkaline lake in southern Alberta. Eighty-three percent of lakes samples had a pH value greater than 7.0 (low sensitivity). The pH ranged from 5.6 to 7.0 in 17% of lakes sampled, while pH values less than 5.5 were found in only 1% of the lakes. The lowest modal classes (pH 6.6 to 7.0) were found in the northern regions. The Canadian Shield and Grande Prairie regions contained very high proportions (56 and 45%, respectively) of low pH (<7.0) lakes. The regions with the highest modal classes (pH >8.0) were found in the southern half of the province; 97 to 100% of lakes sampled in these regions had pH values greater than 7.0.

4.4 SENSITIVITY MAPS

Sensitivity maps, based on alkalinity and calcium concentrations, and pH values, are presented in Figures 2 to 4.

Based on alkalinity, lakes found in the Birch Mountains area of the Fort McMurray region, and most of the lakes in the Caribou Mountains region, are categorized as moderately to highly sensitive ($<20\ \mathrm{mg \cdot L^{-1}}$). Large areas containing sensitive lakes were also found in the Jasper National Park region and in the Canadian Shield region. Small numbers of sensitive lakes occur, though rather infrequently, around Lesser Slave Lake in the Swan Hills region, and within Waterton National Park (Figure 2).

Areas containing lakes that were moderately to highly sensitive based on calcium values included all of the Caribou Mountains region, sections of the Birch Mountain and Muskeg Mountain uplands in the Fort McMurray region, and the Canadian Shield region around Lake Athabasca. Localized areas that can be considered sensitive to acidification were found in the Grande Prairie and Swan Hills regions and in the Jasper and Waterton national parks regions (Figure 3).

Table 4. Summary statistics of pH values for Alberta regions.

Region	n	Modal Class	Range
South Alberta	75 (76)[a]	>8.0	7.0 to 10.6
South-Central	45 (57)	>8.0	7.5 to 10.0
Lakeland	80 (84)	>8.0	7.6 to 9.4
Fort McMurray	75 (75)	>8.0	6.1 to 10.0
Wood Buffalo	91 (91)	7.6 to 8.0	3.4 to 8.6
Canadian Shield	116 (116)	6.6 to 7.0	5.1 to 8.5
Red Deer-Calgary	35 (35)	7.6 to 8.0	7.0 to 8.6
Edson	47 (52)	>8.0	6.5 to 8.7
Swan Hills	87 (87)	7.6 to 8.0	4.4 to 9.4
Caribou Mountains	40 (40)	7.1 to 7.5	5.9 to 8.6
Grande Prairie	78 (78)	6.6 to 7.0	5.6 to 9.4
Jasper	101 (101)	7.6 to 8.0	6.0 to 8.7
Banff	64 (64)	7.6 to 8.0	7.4 to 8.5
Waterton	26 (26)	7.6 to 8.0	7.0 to 9.8

[a] Number of lakes with pH data (total number of lakes).

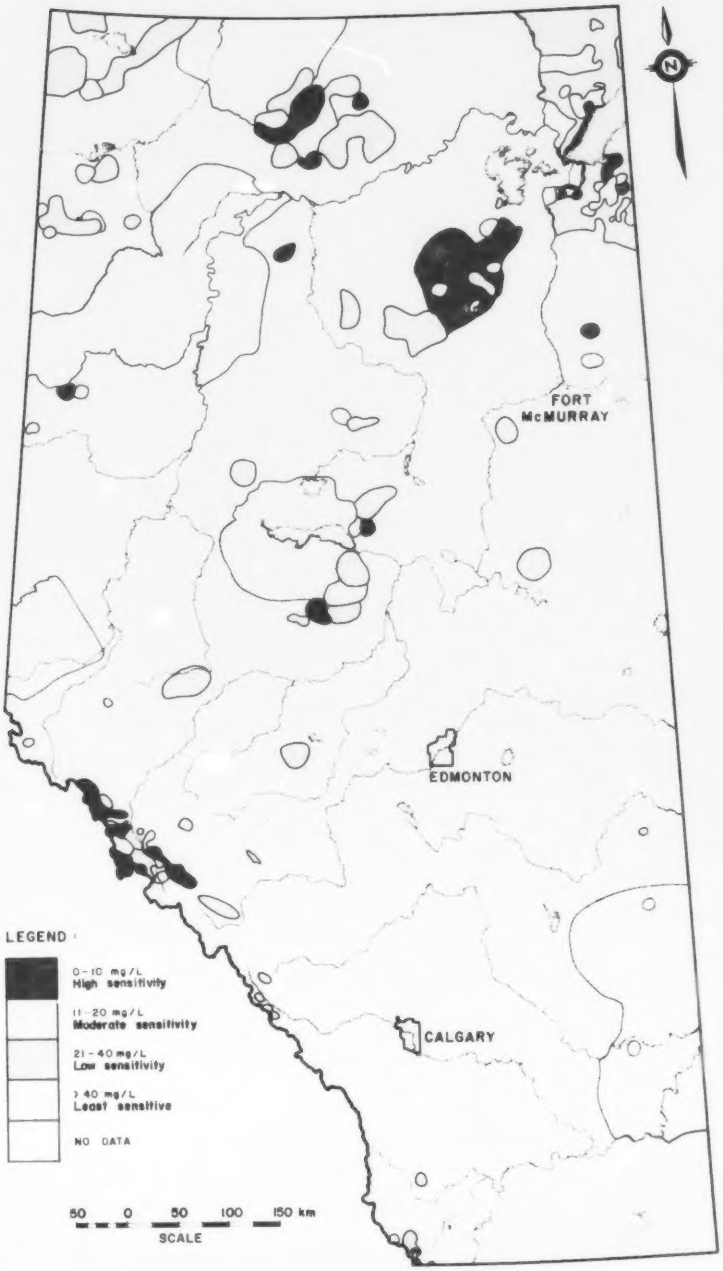
FORT McMURRAY
EDMONTON
CALGARY
LEGEND:
0-10 mg/L High sensitivity
11-20 mg/L Moderate sensitivity
21-40 mg/L Low sensitivity
> 40 mg/L Least sensitive
NO DATA
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Figure 2. Sensitivity of Alberta lakes to acidification as determined by alkalinity values.

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Water Quality Control Branch

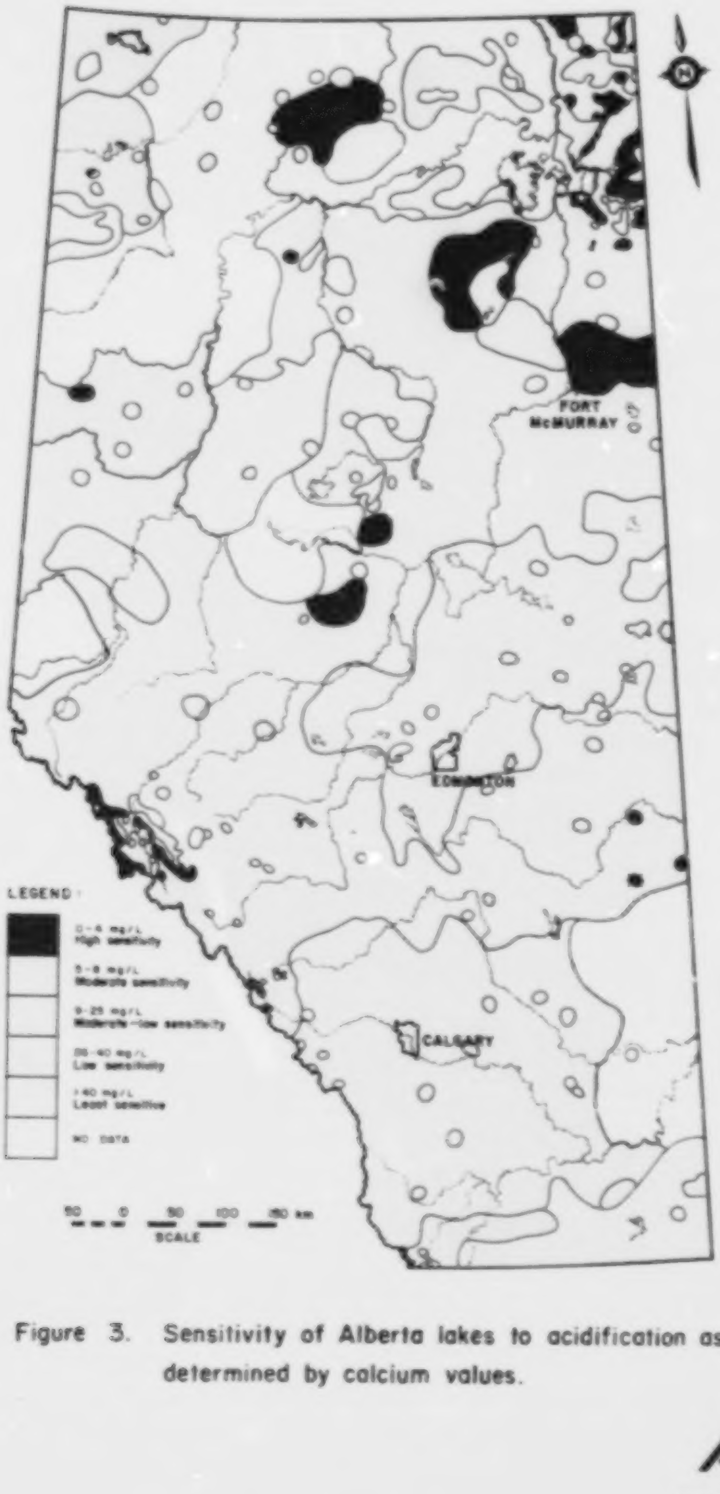
FORT McMURRAY
EDMONTON
CALGARY
LEGEND:
0-4 mg/L
High sensitivity
5-8 mg/L
Moderate sensitivity
9-25 mg/L
Moderate-low sensitivity
26-40 mg/L
Low sensitivity
>40 mg/L
Least sensitive
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Figure 3. Sensitivity of Alberta lakes to acidification as determined by calcium values.

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Pollution Control Division
Water Quality Control Branch

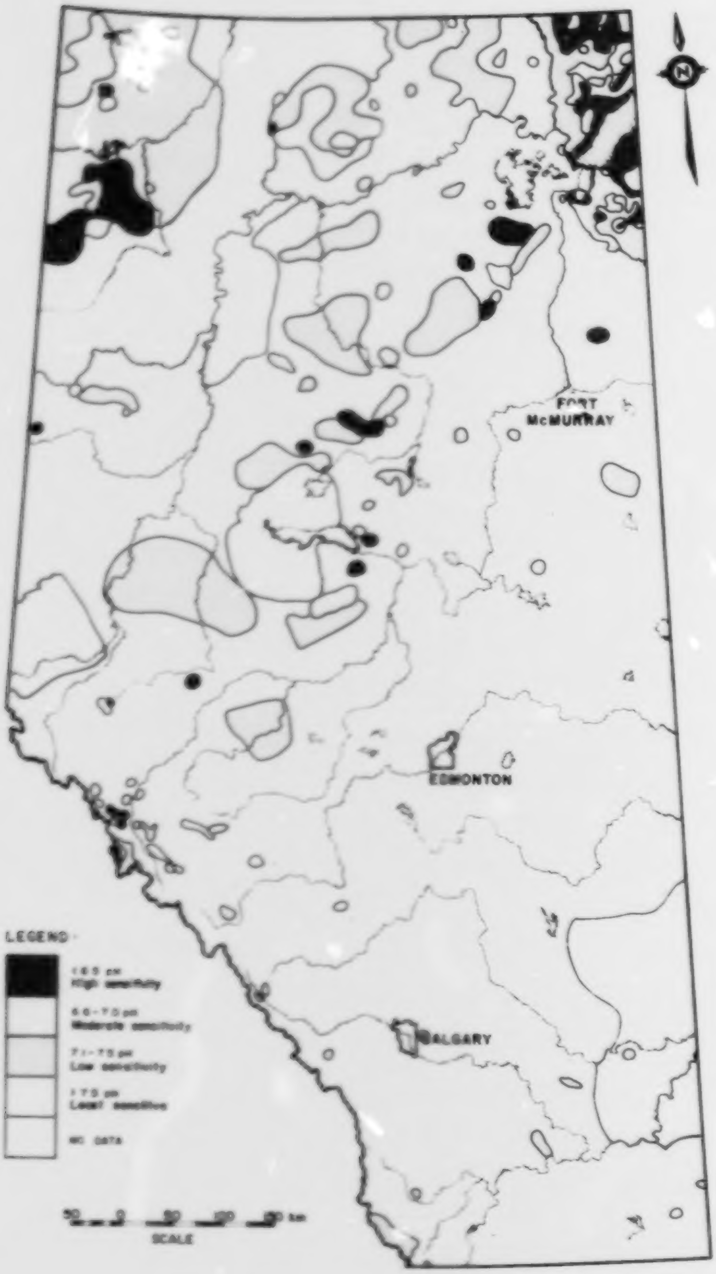
N
FORT McMURRAY
EDMONTON
CALGARY
LEGEND
High sensitivity
6.6 - 7.0 pH
Moderate sensitivity
7.1 - 7.5 pH
Low sensitivity
Least sensitive
NO DATA
50 0 50 100 150 km
SCALE

Figure 4. Sensivity of Alberta lakes to acidification as determined by pH values.

Alberta
ENVIRONMENT
Pollution Control Division
Water Quality Control Branch

The total land area of the province with lakes of low pH (<7.0) was slightly smaller than the area with lakes of low calcium or low alkalinity; however, similar regions were involved. The areas dominated by lakes with low pH included the Canadian Shield region, the southern part of the Caribou Mountain region, and uplands of the Grande Prairie region (Figure 4).

5. DISCUSSION

The potential impact of acid deposition on aquatic ecosystems is dependent upon the interactions of a number of geological, hydrological, topographical, and pedological factors within the ecosystem and surrounding watershed, and their subsequent influence on the chemistry of the waters. In order to identify sensitive or potentially sensitive lakes in Alberta, it is necessary to examine the chemical variables chosen as sensitive indicators (alkalinity, calcium, pH) in relation to some or all of the above factors.

Lakes situated in the southern regions of Alberta are generally well buffered, and hence, rather insensitive to the effects of acid deposition. The presence of carbonate-rich bedrock overlain by calcareous tills is reflected in the high alkalinity values of lakes in these regions. Calcium and magnesium bicarbonate waters predominate except in the south-central region where the ionic contents of highly saline lakes are dominated by sulphate and sodium. Within this region, three lakes, that could be classified as sensitive based on their low calcium values, are actually well buffered due to the presence of sodium bicarbonate, and their alkalinity values are among the highest in the province (6080 and 24 394 $mg.L^{-1}$).

The most potentially sensitive lakes in the province, as indicated by the sensitivity criteria chosen for this study, are situated in the Rocky Mountain National Parks and northern regions. The influence of geology on water chemistry is most apparent in the Canadian Shield region. Hendrey et al. (1979) and Norton (1980) classified geologic areas like the Shield as highly to moderately sensitive to acid deposition. This area is underlain primarily by siliceous bedrock, such as granite, gneisses, and quartzitic sandstones, which is highly resistant to weathering and contributes little to the ionic balance of surface waters (Likens et al. 1979). However, chemistries of the Shield lakes examined in the present study were highly varied and reflected a broad range of buffering capacities due to local variations in geology. Calcium, found in pyroxene, amphiboles (such as horneblende and amphibolites), and plagioclastic feldspars (Fairbridge 1972), was the dominant cation in most Shield lakes, with magnesium and sodium of less, but significant, importance. Although calcium is usually associated with magnesium, sodium was present in equal or greater proportions than magnesium in many lakes. Bicarbonate was the major anion in most lakes, although sulphate and chloride played major roles in some lakes underlain by chloritized porphyritic biotite granites, chloritic schists, and epidotes.

Over 64% of lakes on the Canadian Shield had low calcium values, indicating high to moderate sensitivity, but only 18% of these had alkalinity values of the same rating. The higher alkalinity values may be related to the contributions of magnesium bicarbonate in mafic materials, such as olivine, horneblendes, and garnetiferous granites, and to sodium bicarbonate in feldspars and amphiboles. However, the bedrock is not easily weathered, and further inputs of acid deposition may lower lake alkalinity with little appreciable counteracting input of bicarbonate from the surrounding watershed.

In northern regions of the province off the Canadian Shield, the identification of sensitive lakes is complicated by the presence of glacial deposits on the surrounding areas, especially when these do not reflect the lithology of the underlying bedrock. Bedrock geology in most of these regions consists mainly of dark-grey Cretaceous shales, siltstones, limestones, dolomites, sandstones, and concretionary ironstones and bentonite beds (Green 1972) overlain by glacial, glacio-fluvial, or glacial-lacustrine deposits of varying thickness.

Lakes in the Caribou Mountains region lie both on the slopes and plateaus of the hills. On the plateaus, muskeg is extensive and underlain by widespread discontinuous permafrost. Groundwater discharge is diffuse, due to the degeneration of flow systems resulting from extended periods of soil frost, and contributes to streams, lakes, and muskeg. Recharge in the area is mainly through precipitation (Ozoray 1980), and a short residency time in the soils is reflected in the water chemistry. Alkalinity and calcium values indicate that one-third of the lakes on the plateaus are potentially sensitive to the effects of acid inputs.

A regional set of old slump features characterizes the slopes of the Caribou Mountains, and lakes fed by surface water or precipitation are formed between slump blocks and scars. The unexposed shales and tills of these slopes contain sulphur under low redox potential circumstances; slumping and exposure of these slopes results in sulphur oxidation. As a consequence, lake waters are high in sulphate and are extremely well buffered (Ozoray 1980).

In the Wood Buffalo region, lakes are also very well buffered. Approximately two-thirds of lakes sampled were of calcium, magnesium, or calcium-magnesium-bicarbonate type, while waters of one-third of the lakes were of calcium-sulphate type. Bedrock geology and groundwater flow heavily influence surface water chemistry in these lowlands. Calcareous shales and dolomitic limestones contribute great supplies of calcium and magnesium. The sulphate-dominated waters originate from extensive evaporite deposits consisting of gypsum, anhydrite, and salt beds (Green 1972).

In the Grande Prairie region, lakes are well buffered with most waters of the calcium-magnesium bicarbonate type. Muskeg lakes are widespread and most are fed by a short, local groundwater system, through overland flow, and through precipitation. A few of the lakes appear sensitive to acid inputs based on their calcium and pH levels, but alkalinity values indicate they have a sufficient buffering capacity.

The presence of carbonate-rich materials in the soils of the lowland areas of the Fort McMurray region is reflected in the high calcium, pH, and alkalinity values of the calcium-bicarbonate type lakes. The values of these variables are much lower in the upland regions where muskeg and organic deposits are more prevalent. A majority of the lakes in these regions are very shallow, and the concentrations of calcium or bicarbonates necessary to provide sufficient buffering are low.

Most of the lakes in the national parks regions are fed by groundwaters or meltwaters and are of a calcium-magnesium-bicarbonate type. Most mountain lakes that are potentially sensitive to acid inputs are located in the Jasper region. Furthermore, the most sensitive lakes in this region are located at high altitudes. The low chemical values (pH, calcium, alkalinity) at high altitudes in Jasper may be due to the presence of more chemically resistant quartzite rocks, in comparison with a predominance of limestone in Banff (Anderson and Donald 1978).

5.1 WESTERN CANADA

Similar mapping procedures have been instituted in the other western provinces (British Columbia, Saskatchewan, Manitoba). Preliminary results indicate that a number of lakes in all provinces are inadequately buffered against potential inputs of acid deposition.

In British Columbia, the most sensitive waters, based on alkalinity values, are located in the Kelowna and Kamloops-Shuswap areas, on the lower mainland, and all along the western coast within 150 km of the Pacific Ocean (Clark and Bonham 1982; Sullivan et al. 1985). Many of these areas are located in mountainous watersheds consisting of non-calcareous bedrock overlain by a very thin covering of soil with little buffering capacity; they also coincide with valuable Pacific salmon spawning grounds. Some of these areas are presently receiving acid precipitation of pH 5.0 or lower (Nikleva 1982); studies have suggested that these low pH values are associated with anthropogenic emissions from the British Columbia lower mainland and Washington State. A continuation of these emissions may seriously impact these sensitive waters and the salmon stock inhabiting them.

Preliminary studies in Saskatchewan (Liaw 1982; Liaw and Atton 1981) and in Manitoba have indicated that potentially sensitive lakes are located on the Canadian Shield, which covers the northern half of both provinces. The Shield is comprised of the Athabasca Plains and the Precambrian basement. The Athabasca Plains, a large oval area underlying a significant portion of northern Saskatchewan, is composed of coarse-grained quartzitic sandstones, overlain by sandy drift. The bedrock and overlying materials have minimal buffering capacity and lakes in this area are classifed as highly sensitive to acid inputs. The Precambrian basement rocks surround the Athabasca Plains and underlie the remainder of northern Saskatchewan and all of northern Manitoba. They are primarily composed of granitic-plutonic rocks, granite gneisses, and softer metasediments; overlying materials consist of thin organic layers and lichen growth. Many of the soils in these regions are strongly acid and have low buffering capacity. Acid inputs draining through these soils to lakes and streams would not be neutralized, and lakes in these regions are considered moderately to highly sensitive to acid inputs.

5.2 ACIDIFICATION MODELS APPLIED TO ALBERTA LAKES

There is an increasing awareness of the complexity of lake biogeochemistry and the resultant difficulties associated with modelling lake acidification. Historical data are frequently lacking and a number of models have been developed to overcome this deficiency. A quantitative model proposed by Almer et al. (1978) delineates the degree of acidification by comparing the observed relationship between measured concentrations of alkalinity and calcium plus magnesium with the theoretical relationship. These authors have shown that oligotrophic waters unaffected by acid deposition contain proportional amounts of calcium plus magnesium and alkalinity.

During acidification, cations are mobilized within the watershed and sulphate replaces bicarbonate in lake water, resulting in an altered cation balance in which bicarbonate is reduced for a given concentration of calcium plus magnesium; acidification can thus be recognized as the loss of alkalinity that has occurred.

Lake data from various regions in Alberta were fitted to this model (Figure 5). A departure below the theoretical 1:1 ratio would indicate an increase in bicarbonate consumption in response to mineral acid loading, or increased calcium plus magnesium values due to leaching (Henriksen 1982). The vertical distance from the 1:1 line indicates the degree of acidification that has occurred; lakes lying on the x-axis, with an alkalinity of zero, are considered acidified.

Only those Alberta lakes with alkalinity values <500 $\mu eq \cdot L^{-1}$ (30.5 $mg \cdot L^{-1}$), thus indicating high to moderate sensitivity, were included in the plot. About 50% of selected lakes in the Fort McMurray, Grande Prairie, and Canadian Shield regions lie below the 1:1 line, indicating an alkalinity deficiency; most would require a loss of 150 to 200 $\mu eq \cdot L^{-1}$ of alkalinity to be considered acidified. All selected lakes in the Rocky Mountain national parks and Wood Buffalo regions exhibited deficiencies in alkalinity. Lakes in the Jasper region appear to be the most sensitive in the province, and a

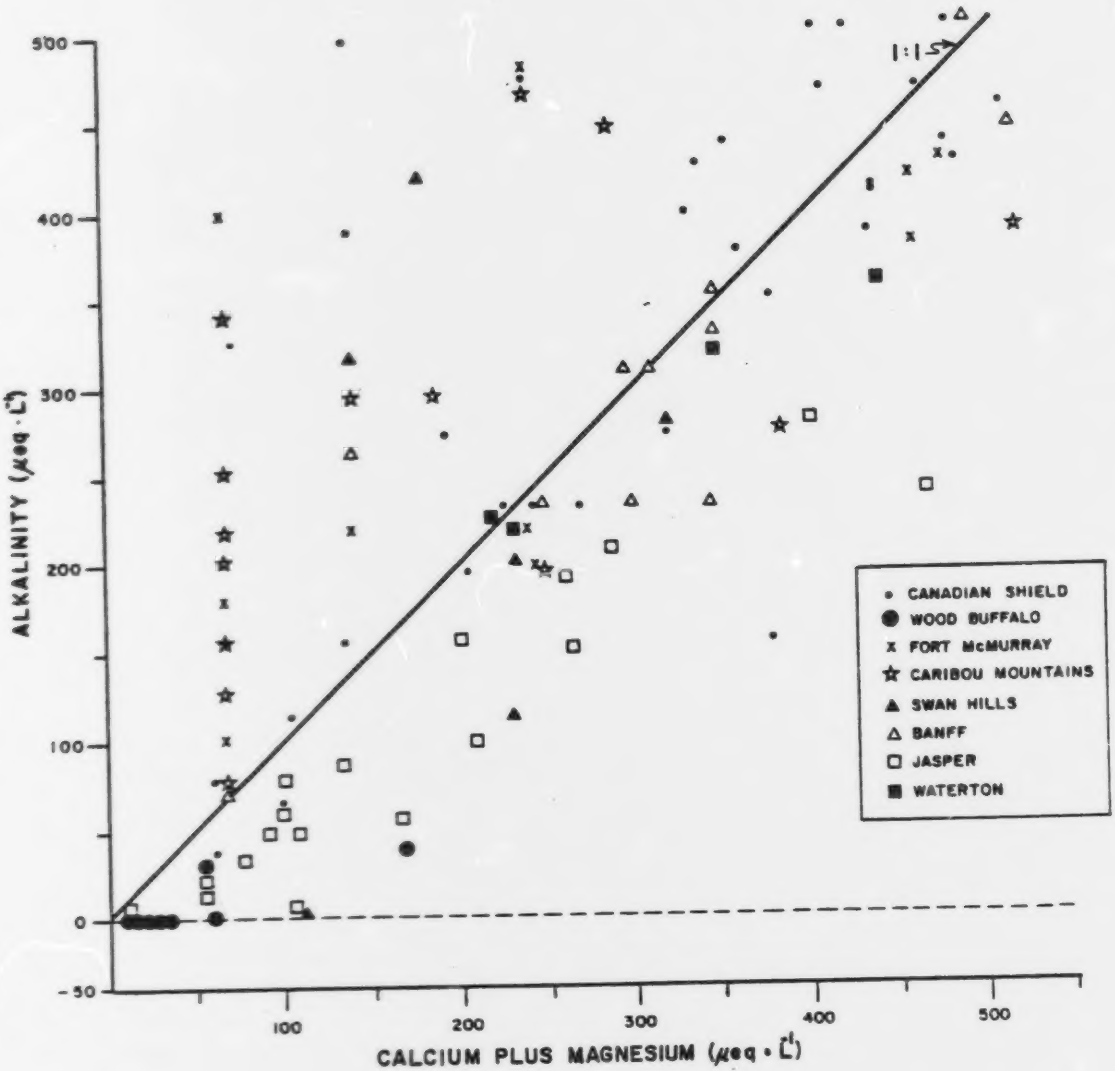

Figure 5. Total concentration of alkalinity with respect to calcium-plus-magnesium for some Alberta lakes. Solid line represents theoretical relationship for lakes unaffected by acid deposition.

further decline in alkalinity of 4 to 100 $\mu eq \cdot L^{-1}$ would be sufficient to acidify 12 of the lakes.

Eight of nine Wood Buffalo lakes lie on the x-axis and are considered acidified; these are small upland, muskeg-fed lakes with no evidence of human impact. The organic-rich soils in these areas produce highly acid waters due to high concentrations of organic acids. The effect of cation exchange in these waters is likely small. The organic acids and alkalinity, resulting from sulphate reduction and nitrate uptake, provide a strong buffering mechanism against the inputs of mineral acidity in the form of acid deposition (Hemond 1980). Thus, these waters would probably not be altered further by acid deposition because they are buffered, although in the acid range (pH <4.5; Hemond 1980).

A second model, proposed by Henriksen (1980), functions as a predictive nomogram and is based on the hypothesis that acidified waters are the result of a large-scale base titration. He compared the concentration of calcium-plus-magnesium, which is used as a surrogate for original alkalinity, with lake water sulphate concentration, which is used as a surrogate for acidification, to obtain linear correlations. The nomograph separates lakes into three groups: bicarbonate lakes (pH >5.3), transition lakes (pH 4.7 to 5.3), and acid lakes (pH <4.7), and relates the stages of acidification to levels of precipitation pH (Figure 6).

Of 98 Alberta lakes examined, 85 were classified as bicarbonate lakes, 6 were in transition, and 7 were considered acid. The nomogram correctly predicted the measured pH of most lakes, except certain lakes in Jasper which had much higher measured pH values than would have been expected. Some transition lakes in all regions also had higher than expected pH values.

Although both the alkalinity versus calcium plus magnesium model and the nomogram have demonstrated validity for the Scandinavian lakes for which they were developed (Henriksen 1979; National Research Council of Canada 1981), there is some reservation concerning their general applicability to Eastern North American waters (Church and Galloway 1984; Wright 1984). Both models carry certain assumptions which must be carefully considered when attempting to apply them to Alberta lakes.

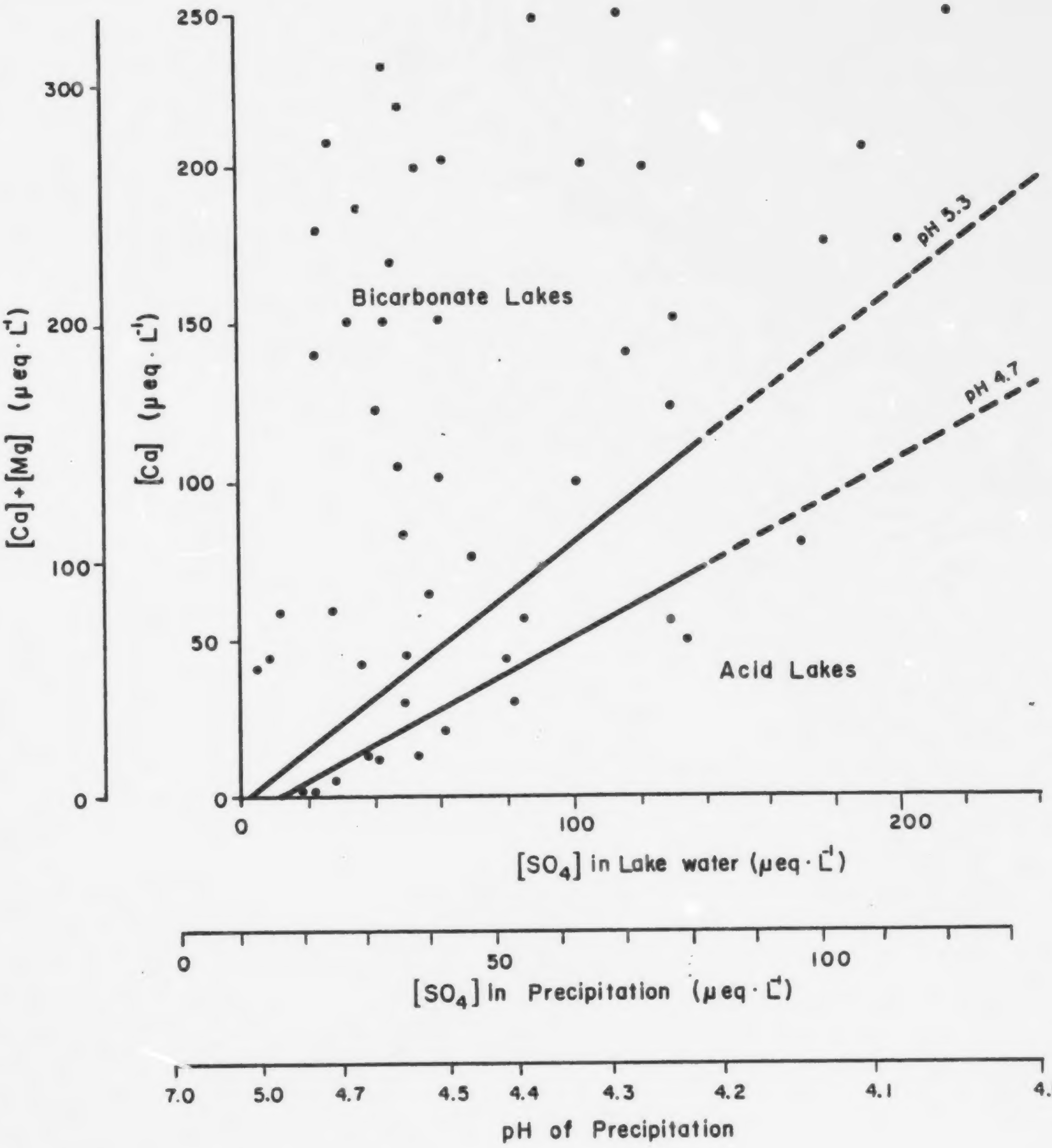

Figure 6. Henriksen's nomogram for the prediction of lake acidification status.

A primary assumption of both models is that they are intended for use with pristine, oligotrophic waters containing low levels of organic acids. Decreased levels of bicarbonate alkalinity in a lake may suggest that it is indeed acidifying, but this change does not preclude the possibility that other buffering systems besides the bicarbonate-carbonate-carbonic acid system are operating and contributing to titratable alkalinity. These systems may include weak organic acids (humic and fulvic), or other hydroxide complexes of metals such as aluminum and iron. The complexing of calcium plus magnesium with dissolved organic matter may also result in an overestimate of ionic calcium plus magnesium, as the organically bound cations would be measured. The presence of organic acids may disturb the basic relationship between cations, alkalinity, and pH, making it difficult to isolate the roles of mineral acids and organic acids in acidification.

A second consideration of these models is that of steady state. This assumes that chemical observations (e.g., calcium, magnesium, alkalinity, and sulphate concentrations and pH) represent a constant condition at the time of sampling and that no one component changes at a rate different from the others (Church and Galloway 1984). These models assume that calcium-plus-magnesium is proportional to alkalinity under conditions of carbonic acid weathering, and that these two cations would remain conservative under deposition of mineral acids, which would allow a prediction of pre-acidification alkalinity based on cation content. However, increases in these cations can occur in lake water due to leaching from the surrounding watershed (National Research Council of Alberta 1981). Furthermore, the natural occurrence of sodium/magnesium-bicarbonate/sulphate type waters rather than calcium-bicarbonate (as is commonly encountered in Alberta) may influence results.

These models are still being evaluated with respect to their general applicability to European and North American waters. All relevant factors should be considered carefully before using them to identify sensitive lakes in Alberta.

6. CONCLUSION

The sensitivities of 982 Alberta lakes to acid deposition were assessed using the three criteria of calcium, alkalinity, and pH. Based upon the alkalinity data, 9.7% of the total lake sample was classified as moderately to highly sensitive. These lakes are situated in the Rocky Mountain National Parks, the Canadian Shield, and various upland areas in the northern part of the province. Sensitivity maps were prepared in order to fulfill Alberta's obligation to the mapping of Western Canadian aquatic ecosystems.

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MICROBIOLOGICAL STUDIES OF LAKES RECEIVING ACID DEPOSITION

by

Salem S. Rao[1] and B. Kent Burnison[1]

ABSTRACT

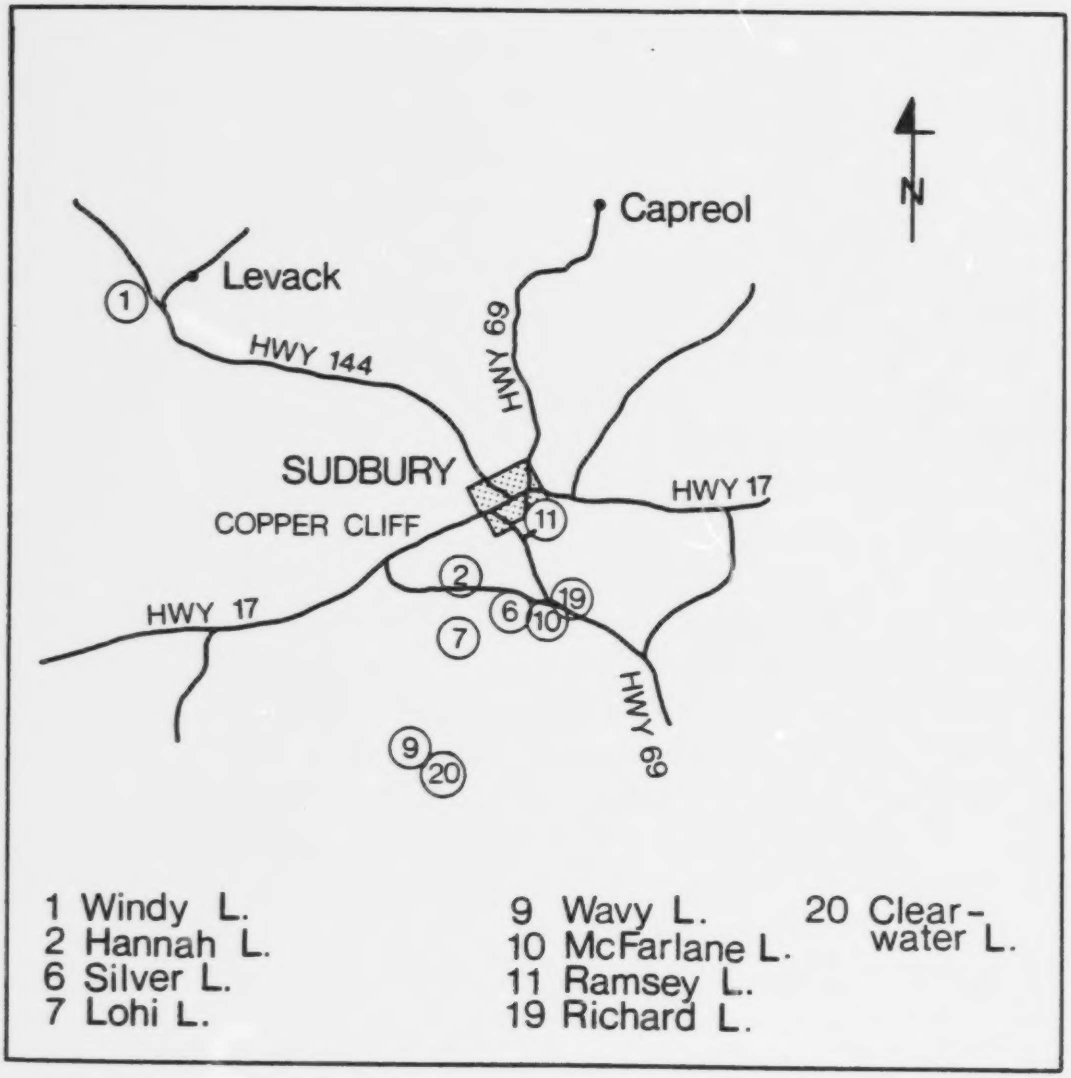
A summary of bacteriological data collected for water and sediment cores from some Ontario lakes receiving acid deposition indicates that bacterial populations and activities were diminished by 20-30% under acidic conditions. A pH value below 5.5 appeared to be critical for active populations. Measurements such as direct counts of total and respiring bacteria, heterotrophic plate counts, nitrifying and sulphur cycle bacteria, microbial activities (O_2 consumption rates and organic substrate utilization), and bacterial morphology and physiology were considered. An ultrastructural analysis is shown to differentiate between different levels of acid stress and combined acid/toxic metal stress under laboratory conditions. Data, methodology, and some implications of the studies are presented.

[1] National Water Research Institute, Burlington, ON

1. INTRODUCTION

During the last two decades it has become evident that precipitation over the Eastern U.S. and Canada has become increasingly acidic (Almer et al. 1978). The concern for the impacts of acid deposition on aquatic ecosystems has led to several biogeochemical studies in Ontario and Eastern Canada (Nriagu 1984). Some of the lakes near Sudbury, Ontario exhibit wide diversity in geochemical and biological characteristics and show varying degrees of stress from acid precipitation (Gorham and Gordon 1960; Beamish and Harvey 1972; Conroy et al. 1978). Acid rainfall (pH 4.0 to 5.0) has become a common event and one that is deleterious to many aquatic ecosystems (Haines 1981; Wright and Gjessing 1976). In lakes, bacteria are an important component of the biota in terms of biomass and nutrient regeneration activity (Wetzel 1983). Bacterial activity can, in some cases, regulate the rate of lake acidification (Kelly et al. 1982). The effect of acidity on microbial activity in aquatic ecosystems has generated a lot of interest recently (Leivestad et al. 1976; Alexander 1978; Traaen 1980; Pagel 1981; Fjeringstad and Nilssen 1982; Kelly et al. 1982). In general, the field surveys show that bacterial populations and activity were lower in acidified lakes than in non-acidified lakes (Babich and Stotzky 1978). Following such observations, some laboratory studies were made to ascertain the effects of acid stress on bacterial isolates (Baker et al. 1982, 1983) or samples obtained from artificially acidified water (Baath et al. 1979). Few previous studies have related the bacterial activity to the in situ pH of the sediments.

The goal of this article is to explore the nature and extent of the effects of acid deposition on lake bacteria in some Ontario lakes (Figure 1) and the use of these populations from lake sediments as indicators of acid stress. Emphasis is placed on those parameters that correlate with the diminished capacity for degrading organic materials. The philosophy and ideas that form the basis for our studies here in Ontario may be applicable to developing studies on lakes receiving acid deposition in Western Canada.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1 Windy L.
2 Hannah L.
6 Silver L.
7 Lohi L.
9 Wavy L.
10 McFarlane L.
11 Ramsey L.
19 Richard L.
20 Clearwater L.

Figure 1. Microbiology sampling sites in lakes receiving acid precipitation near Sudbury, Ontario. (From Rao et al. 1984a)

The contents of this review article are extracted from the following scientific publications: Rao and Dutka (1983); Rao et al. (1984a,b); Burnison et al. (1986); and Leppard and Rao (1986).

2. MATERIALS AND METHODS

2.1 STUDY SITE

The lakes examined are located within a 30 km radius from the smelters in Sudbury, Ontario (Figure 1). These Precambrian Shield lakes encompass a wide diversity of physical and chemical characteristics and show varying degrees of stress from acid rain (Nriagu et al. 1982). Acidity of the lakes can be traced back to acid rain. The details of the geological settings and the general limnology of lakes in the region have been outlined by Conroy et al. (1978).

2.2 SAMPLE COLLECTION

Surface water samples (1 L) from a series of eight lakes (Figure 1) were collected in sterile containers. These samples were packed in ice and transported within 48 h to our laboratory for further processing. This procedure did not affect the levels of bacterial populations (Rao and Dutka 1983). The studies were usually carried out during May through October. Sediment cores (50 cm x 6 cm) were collected by means of a lightweight coring device (Williams and Pashley 1979). Only cores that came up with their sediment-water interfaces intact and undeformed were subsectioned and processed within one hour after retrieval. Each core was subsectioned at 1 to 2 cm intervals up to 40 cm. The samples were collected in sterile plastic bags and refrigerated immediately. The samples were processed within 48 h in the shore laboratory.

The pH measurements were made using a portable pH meter with the electrodes inserted directly into the mud. Organic content of the sediments was measured by combustion [loss on ignition (LOI)] according to standard procedure (American Public Health Association 1980).

2.3 BACTERIOLOGICAL PROCEDURE

Counting of bacteria was performed using epifluorescence microscopy after staining with acridine orange. The staining of filters and solutions used followed Zimmerman et al. (1978).

Total and actively respiring bacterial populations were estimated microscopically on all water samples using the combined acridine orange INT-formazan reduction technique (Zimmerman et al. 1978). Reduction of the tetrazolium dye in bacterial cells involves respiration. In actively respiring bacteria, deposits of accumulated reduced INT-formazan are seen as optically dense, dark red intercellular spots, which can be viewed using light microscope observation (Zimmerman et al. 1978). Total bacteria were estimated on the same slide using UV light. Numbers of bacteria were determined in 20 ocular fields, resulting in a total count of 30 to 300 bacteria.

Aerobic heterotrophic bacteria were measured in all samples using the spread plate procedure and a low-nutrient medium. Incubation of the inoculated plates was for seven days at 20°C (Dutka 1978).

2.4 OXYGEN CONSUMPTION RATE

Oxygen consumption by the various sediment fractions from the lakes was measured at 20°C using a Gilson differential respirometer. Each Warburg flask contained 3 g of sediment (wet weight), 2 mL of filter sterilized lake water, which served as diluent, and 0.2 mL of 20% KOH in the centre well for carbon dioxide absorption. A pre-incubation period of 15 min was used in all experiments. No exogenous substrate was added. The Warburg flasks were shaken at a rate of 110 strokes per minute to ensure that the oxygen diffusion rate was not a limiting factor. KCN was used to stop microbial activity. By calculating the difference between total oxygen uptake and oxygen uptake obtained by the KCN poisoning, microbial oxygen uptake was determined.

2.5 HETEROTROPHIC ACTIVITY METHOD

Heterotrophic activity measurements were made using modifications of Harrison et al. (1971). Sediment (0.5 mL) was suspended with 10 mL of filter (0.2 μm) sterilized lake water. Various aliquots of an 18.5 kBq/mL solution of uniformly labelled ^{14}C-glucose or ^{14}C-glutamic acid (Amersham, specific activity 10 and 10.4 GBq/mmol, respectively) were added to combusted (450°C for 2 hours) glass serum bottles. All concentrations were run in duplicate. Five millilitres of filter sterilized lake water was then added. At zero time, 0.5 mL of the diluted sediment slurry was added to each bottle. Appropriate killed-controls consisted of adding 100 µL of formaldehyde before the addition of sediment. The respiration cup assembly, with a 2.5 cm x 5.0 cm accordion-folded piece of filter paper (Whatman No. 1) in the cup, was used as the bottle stopper. The bottles were incubated in the dark for one hour at 20°C. At the end of the incubation, 200 µL of 5 N H_2SO_4 was added to each bottle to stop further isotope uptake and release the $^{14}CO_2$ from the aqueous phase. β-Phenethylamine (200 µL) was carefully added to the cup assembly. The CO_2 was allowed to evolve for 2 h, the bottles were uncapped, and the filter paper added to a scintillation vial containing 10 mL of ACS II (Amersham). The vials were counted on a liquid scintillation counter using an external standard for quench correction.

The suspended sediments were collected on 0.45 µm Sartorius membrane filters (25 mm). Distilled water (10 mL) was used to wash the residue from the bottles, rinse the filter funnels, and rim the edges of the filters after the funnel had been removed. The filters were placed in glass scintillation vials, 10 mL ACS II was added, and the filters were allowed to dissolve. The sediment was dispersed with a Sonic Dismembrator (Model 150, Artek Systems Corp.) at the full power setting. Five millilitres of water was then added to the sediment suspension, mixed vigorously, and counted as above (Burnisol et al. 1986).

2.6 ORGANIC SUBSTRATE UTILIZATION

Indigenous bacterial populations taken directly as inoculum from the two lakes at the extremities of our selected pH range (Silver Lake, ca. pH 4.0 and McFarlane Lake ca. pH 7.0) were harvested from 48 h batch cultures (at room temperature) in half-strength nutrient broth at pH 4.0 and pH 7.2. Cells were washed three times with filter-sterilized, low-response water and harvested by centrifugation at 10 g x 1000 g for 20 min at 4°C. These washed cells were resuspended (40 mL) for the organic substrate utilization studies. Bacterial respiration using three substrates (glucose, glutamic acid, and sodium acetate) at 5 μmol of substrate per flask was determined using a Gilson differential respirometer at 20°C. Respiration studies were performed in duplicate. Data were corrected for endogenous respiration. Respiration was used to infer the bacterial activity index.

2.7 MORPHOLOGICAL STUDIES

The chemical preparation of the samples for electron microscopy and the analysis of sections was done according to Leppard et al. (1977), but with one change: the phosphate buffer was replaced by cacodylate-HCl buffer. Counterstaining of epoxy-embedded samples (Spurr 1969) and the mode of analysis of ultrathin sections (50 nm to 70 nm) was done according to Burnison and Leppard (1983). Observations and photographs were made with a Philips 300 transmission electron microscope (TEM).

3. RESULTS AND DISCUSSION

Figure 2 is a scattergram showing the representative relationship between bacterial populations and pH in waters of the eight lakes studied. The pH values of these lakes did not change significantly during the study period of May to October. Total bacterial densities were in the 10^6 mL^{-1} range in all lakes examined. Acid stress had no apparent effect on total bacteria since lakes having a pH of 7.8 had total bacterial populations somewhat similar to lakes with pH 3.8. These data confirm earlier observations by Traaen (1980) and Boylen et al. (1983), who showed no consistent relationship between total counts and water acidity.

In contrast, respiring bacteria and aerobic heterotrophs showed a definite response to environmental pH changes. Generally, maximum respiring bacteria recorded in these lakes were in the 10^5 mL^{-1} range, while aerobic heterotrophs recorded were in the 10^4 mL^{-1} range. The pH values below about 5.5 may be critical for these populations.

The aerobic heterotrophic count dropped significantly around pH 5.5. The low-nutrient media used a pH of 7.0 but we assumed that most bacteria would grow well at this pH. Boylen et al. (1983) isolated bacteria from lakes of various pH values on media at pH 7.0 and 5.0, and found that all colonies grew best on media of higher pH, irrespective of the pH of the lake

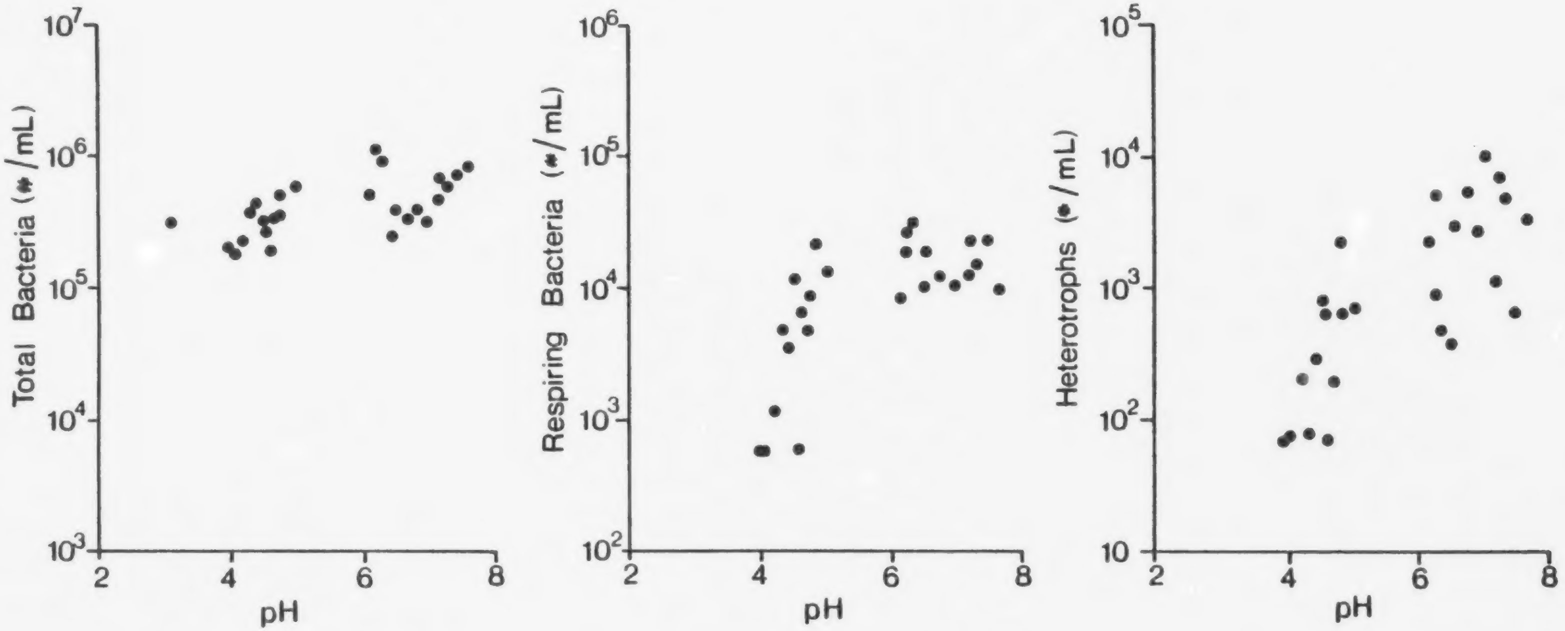


Figure 2. Relationships between bacteria and pH in lake water receiving acid precipitation near Sudbury, Ontario, 1982. (From Rao et al. 1984a).

from which they were collected. Bacteria present in our lakes that are at a pH lower than 5.0 may not necessarily grow at pH 7.0. The lower count that is observed at pH 4 (Figure 2) must be viewed with this reservation.

The respiring bacteria densities also seem to decline around pH 5.5. Visual observations of the INT reduction slides indicate that the bacteria present in lakes with a low pH are smaller than those from a circumneutral pH. The observed decline may be caused by an actual reduction of metabolic activity of bacteria at low pH, or possibly there is a threshold visual limitation to observing a formazan structure inside a very small bacterial cell.

In Figure 3, the pH profiles are compared with changes in aerobic heterotrophs in the lake sediment cores from the acid stressed Silver Lake and the non-acid stressed McFarlane Lake. The aerobic heterotrophic bacterial populations in the top 5 cm layer of sediment cores from Silver Lake (pH of 3.8 to 5.0) number in the 10^3 to 10^4 mL^{-1} range. However, their densities, between 5 and 40 cm where the recorded pH was about 5.5, were relatively larger (10^5 to 10^6 mL^{-1}). In contrast, the profiles of these bacterial populations in the core from non-acid McFarlane Lake declined from about 10^7 mL^{-1} in the surficial sediments with a pH of about 7.1 to about 10^6 mL^{-1} in the deeper layers, where the pH is relatively constant at about 6.5. These data suggest that a pH below about 5.5 appears to be critical for bacterial populations in the sediments.

3.1 MORPHOLOGICAL EFFECTS OF LOW pH ON BACTERIA

A dominant mixed population of bacteria was isolated from non-acid stressed McFarlane Lake and subjected to low pH stress (pH range of 3 to 7). At pH levels of 3, 4, 5, 6, and 7, the culture was repeatedly subcultured to permit its adjustment to the new pH environment. Analysis of structure for populations growing on agar and broth within the pH range of 4 to 7 are summarized in Table 1. Growth was too sparse at pH 3.0 for proper microscopic analysis. Lowering the pH of the aquatic environment seems to increase the complexity of the cell wall-environment interface and the abundance of extracellular materials (Rao et al. 1984b).

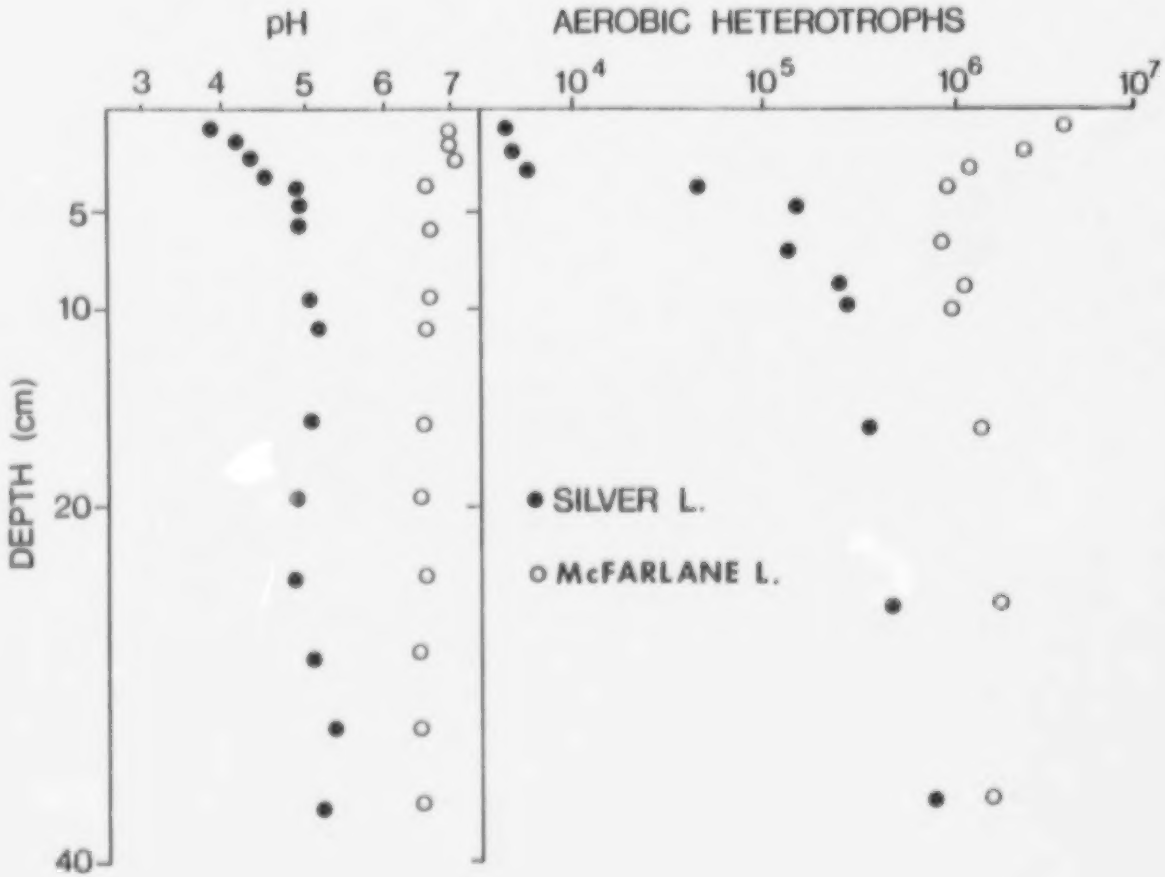


Figure 3. Effects of acid stress on bacterial populations in lake sediments. (From Rao et al. 1984a).

Table 1. The cytological effects of acidity on populations of bacteria isolated from McFarlane Lake.[a]

pH	Shape	Extra-cellular Materials	Interface Cell Wall-Environment[b]	Cytoplasm	Nuclear Region
7	Nearly spherical	Rare	Naked	Extremely dense in agar; various densities in broth	Extremely dense
6	Nearly spherical	Fibrillar structures common	Electron-dense granules	Varied, with many cells having a dense peripheral cytoplasm	Condensed in agar; dispersed in broth
5	Many kinds	Fibrillar structures common, particularly in broth	Electron-dense granules	Varied	Varied
4	Many kinds	Rare	Electron-dense granules	Varied, with many cells having a dense peripheral cytoplasm	Varied

[a] Source: taken from Rao et al. (1984b).

[b] At pH 5 and pH 4, many cells had an outermost electrondense "outer layer" on the cell wall that was particularly evident at pH 4.

Ultrastructural analysis has also been used to differentiate between levels of both acid stress and combined acid/copper stress in laboratory experiments on bacterial enrichment cultures (Leppard and Rao, submitted for publication).

3.2 SEDIMENT MICROBIAL RESPIRATION AND BACTERIAL ORGANIC SUBSTRATE UTILIZATION

One of the effects of lake acidification is reported to be the increased accumulation of organic matter in the lake sediments (Grahn and Hultberg 1974; Grahn et al. 1974; Baker et al. 1982, 1983; Fjerdingstad and Nilssen 1982). Kelly et al. (1984) have shown that decomposition rates of "old" organic carbon are unaffected by pH values as low as 4.0, but newly sedimented material decomposition rates start to decrease at pH 5.25 to 5.0. In Figure 4 the concentration of organic matter in the sediments is compared with the pH of the overlying water for the eight lakes studied. The strong relationship found confirms the results of the previous studies. The buildup of organic matter has been attributed to the inhibition of microbial decomposition processes and/or to a shift from bacterial to less efficient fungal mineralization (Grahn et al. 1974; Baker et al. 1982, 1983; and Fjerdingstad and Nilssen 1982). This increased storage of organic matter in the sediments is tied to the recycling of nutrients and, hence can affect the behaviour of the whole lake ecosystem. This particular facet of lake acidification remains to be investigated in detail.

Figure 5 shows that a strong relationship exists between low pH stress and microbial activity. For example, as the pH decreased, a corresponding decrease in the rate and extent of oxygen utilization and bacterial organic substrate utilization was observed. Maximum uptake at the end of 3 h of incubation in the top 5 cm layer of acid stressed Silver Lake did not exceed 10 to 80 μL O_2.10^{-9} cells.mL^{-1}. However, for the same incubation period in the top 5 cm layer of non-acid stressed McFarlane Lake, oxygen uptake was nearly 10 times more. Somewhat similar observations (3 to 30 times increase) were noticed with regard to indigenous bacterial respiration (organic substrate utilization) from the non-acid McFarlane Lake. Using the INT-formazan reduction technique, at pH 4 no respiring bacteria were

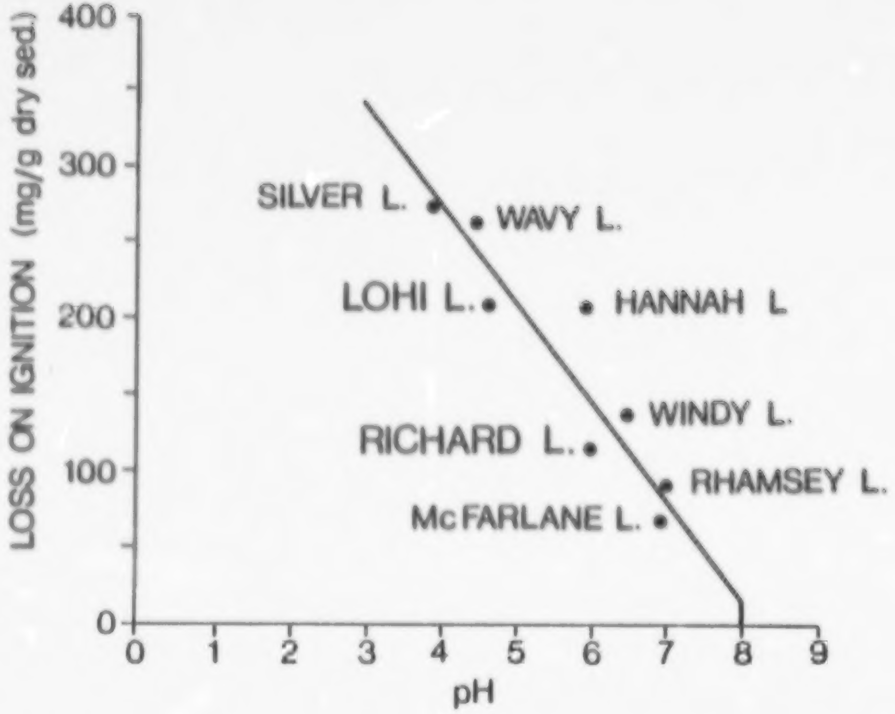
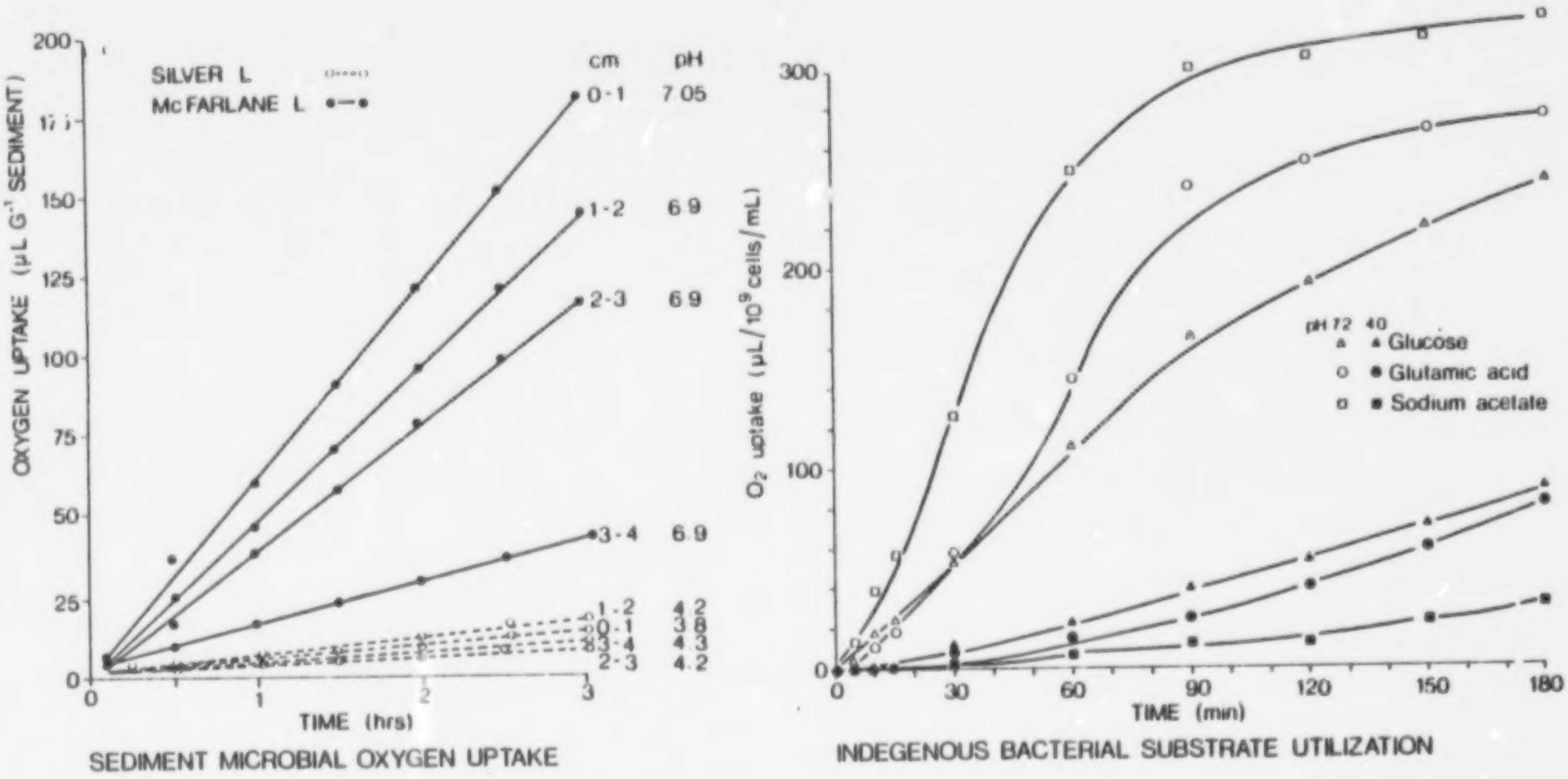


Figure 4. pH and total organics in lake sediments. (From Rao et al. 1984a).



SEDIMENT MICROBIAL OXYGEN UPTAKE

INDEGENOUS BACTERIAL SUBSTRATE UTILIZATION

Figure 5. Microbial activity from acid stressed and non-acid stressed lakes. (From Rao et al. 1984b)

detected at the end of 3 h using any of the three organic substrates. However, under the same conditions, the densities of respiring bacteria were in the range of 10^9 per millilitre when the pH was 7.2. No actively respiring bacteria were detected under severe acid stress conditions. However, this does not necessarily mean such populations were absent; possibly the technique applied did not permit detection of such populations (Rao et al. 1984b).

The heterotrophic activity method of Wright and Hobbie (1965) was used to estimate the level of heterotrophy in the sediments from the three Ontario lakes (Burnison et al. 1986). We have assumed that all the activity was from bacterial origin since we used low levels of substrate. The limitations of the heterotrophic activity procedure can be found in Wright and Burnison (1979). The most important drawback, under the conditions in which the procedure has been used here, is that only one organic compound at a time can be tested and this does not reflect the actual flux of the entire dissolved organic carbon pool, which is a mixture of organic compounds.

Figure 6 illustrates uptake velocites (V_{50}) for ^{14}C-glucose and ^{14}C-glutamic acid in the sediments of the three Ontario lakes studied. Usually glucose uptake is faster than glutamic acid uptake,with the exception of Clearwater Lake (water column pH 4.5) sediment. Two possibilities for this observation are: (1) the bioavailability of the ^{14}C-labelled compound is higher in Clearwater Lake sediment than in the other two sediments or (2) there is an acidophilic bacterial population that is more efficient at taking up glutamic acid. Although the second possibility cannot be completely ignored, we feel that glutamic acid adsorption to calcareous minerals or clay in the circumneutral McFarlane Lake is the most likely explanation. Precise research on the proper adsorption control is still needed (Burnison et al. 1986).

The various observations on the effects of acid precipitation on the microbial population and its activity in lake sediments are summarized in a conceptual model (Figure 7). Lake acidification is surmised to reduce the bacterial activity and hence, increase the organic content of the sediments. These parameters can therefore be used to trace historical changes in the response of lakes to acid precipitation (Rao et al. 1984b).

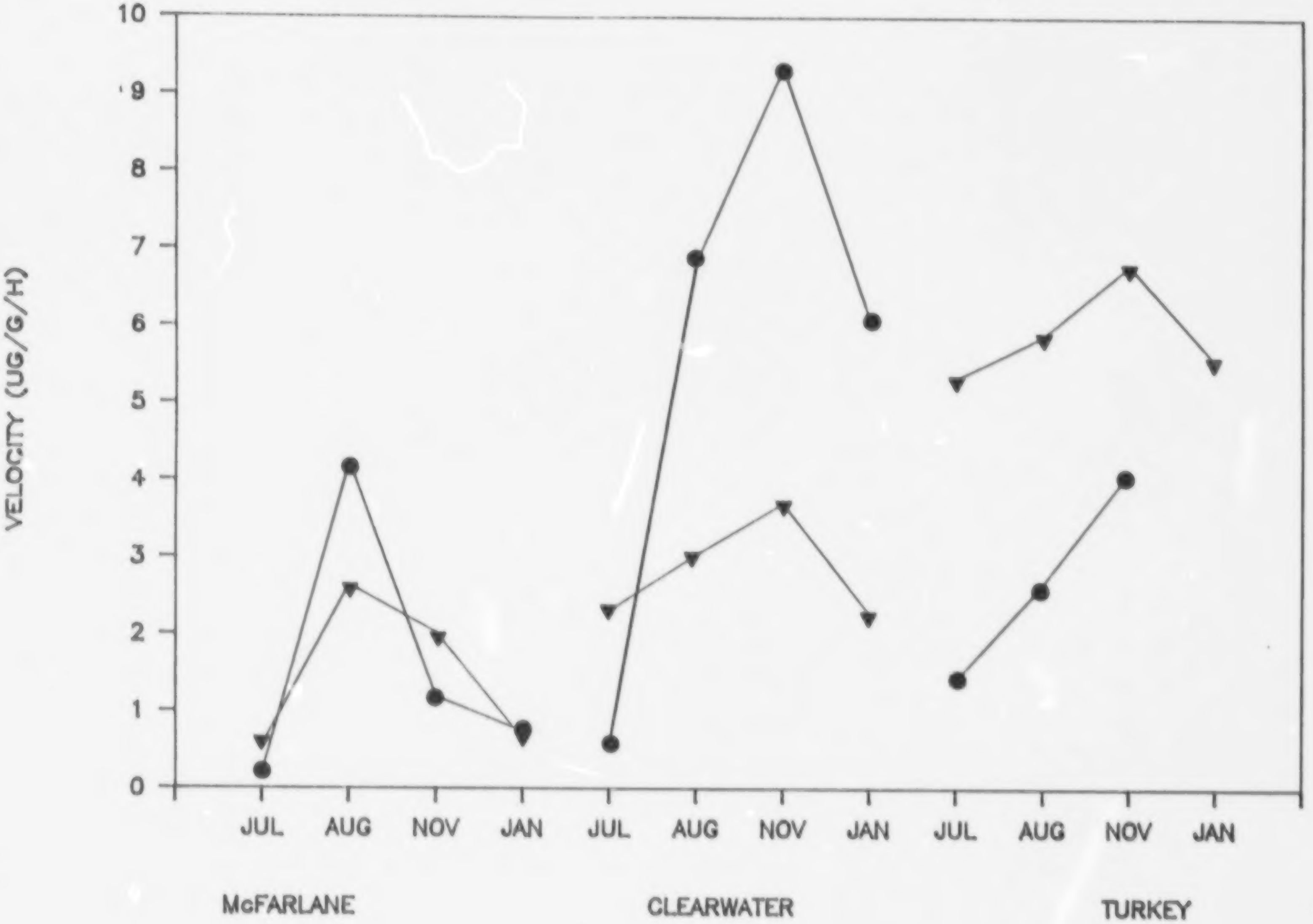
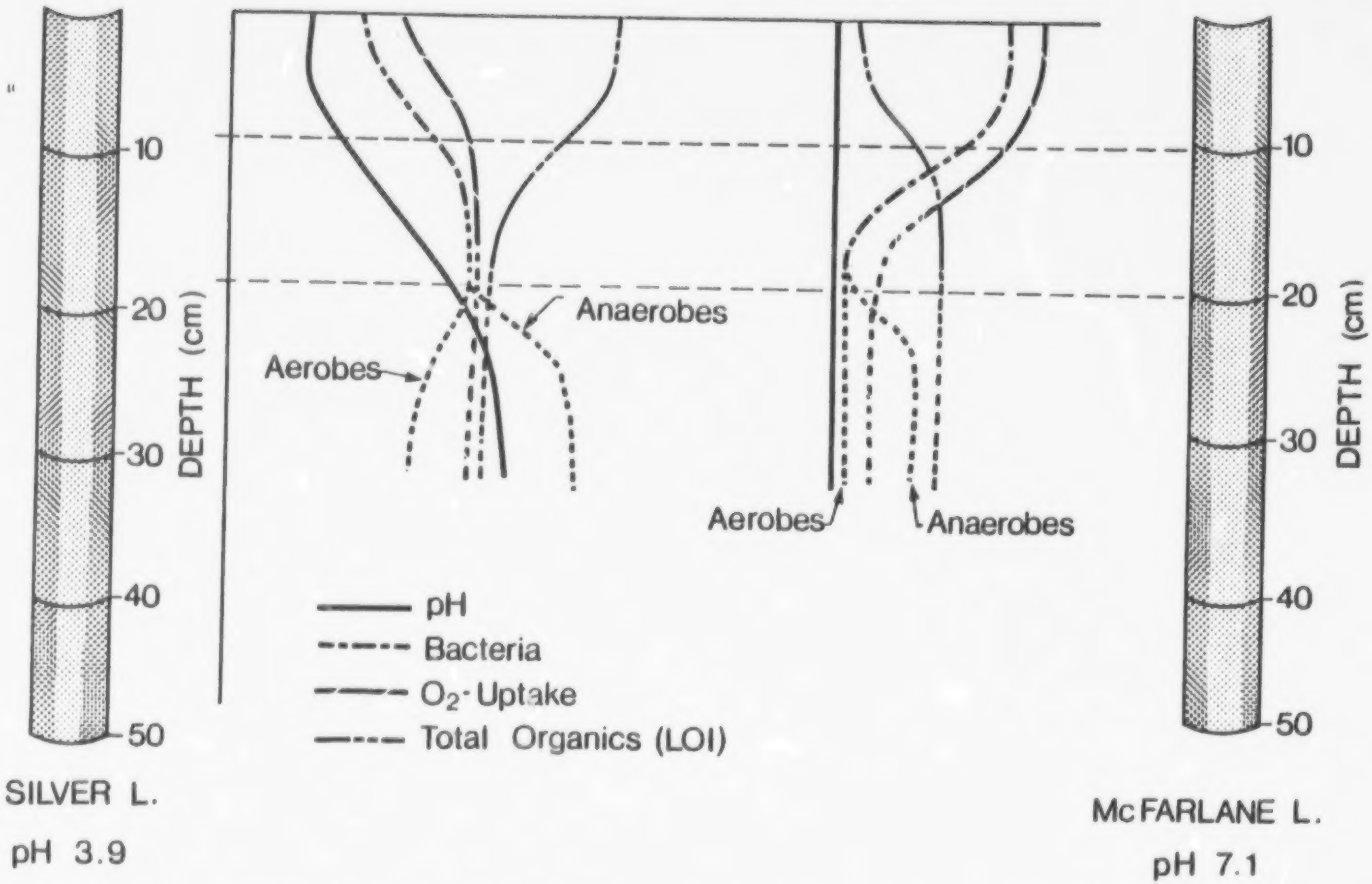


Figure 6. Calculated velocities for glucose (▼) and glutamate (●) at an assumed concentration of 50 μg/L. (From Burnison et al. 1986)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20
30
40
50
DEPTH (cm)
Aerobes
Anaerobes
pH
Bacteria
O_2-Uptake
Total Organics (LOI)
SILVER L.
pH 3.9
Aerobes
Anaerobes
10
20
30
40
50
DEPTH (cm)
McFARLANE L.
pH 7.1

Figure 7. Influence of acid precipitation on bacterial activity in lake sediment (conceptual model). (From Rao et al. 1984a).

4. CONCLUSIONS

Following are the major observations and conclusions from our studies:

1. Bacterial populations and densities were lower in acid stressed lakes than in non-acid stressed lakes.
2. Respiring and heterotrophic bacterial populations in the acid stressed lakes were nearly an order of magnitude less than in the non-acidified lake.
3. A pH value less than 5.5 may be critical for these bacterial populations in sediments and in the water column.
4. A relationship was found between low pH stress and sediment microbial activity.
5. Diminished microbial activity in surface sediments resulted in an increased accumulation of organic matter.
6. The increased storage of organic matter in the sediments is tied into the recycling of nutrients and hence, can affect the behaviour of the whole lake ecosystem.
7. The greatest complexity in terms of bacterial cell structure diversity and development of extracellular products is found at pH 5.0.
8. Low pH stress has a marked effect on bacterial morphology per se and/or the selection of dominant types.
9. Low bacterial activity in acidified lakes may be the result of certain cell structural changes.
10. The physiological alterations in bacteria may be significant as stress indicators if related to cell surface exchange and/or membrane permeability properties associated with nutrient transport or transport of toxic substances.

5. FUTURE STUDIES

Future studies should be sufficiently intensive to establish in detail the extent and the exact nature of the acidification effects on bacterial organic matter degradation rates in lake sediments. Studies on the effects of sulphate and nitrate inputs on microbial organic matter degradation in sediments of lakes receiving acid precipitation should be considered.

Studies should be conducted on acidified lakes where low productivity and low sulphur concentrations exist and on productive lakes receiving high sulphur inputs. Laboratory microcosm studies should be conducted to ascertain the processes by which alkalinity is produced after additions of sulphate and nitrate, thereby reducing the impact of acid rain. In addition, the value of refined microbiological techniques such as the use of ^{14}C-labelled compounds to study various sediment microbiological processes needs to be reassessed.

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METHODOLOGICAL ISSUES IN EVALUATING THE HEALTH EFFECTS OF EXPOSURE TO ACID-FORMING EMISSIONS

by

T.L. Guidotti[1] and M.K.W. Cottle[1]

ABSTRACT

A major challenge in both the design of epidemiologic studies of exposure to toxic agents and interpretation of the findings is to recognize and to accommodate the complex biologic assumptions that underlie population-based research. As part of the initial stages of assessing the feasibility of a proposed study to examine mortality and morbidity in the sour-gas industry, among other industries of interest in Alberta, we examined these relationships critically in an effort to build a simple but generalizable model of epidemiologic associations based on toxicologic principles. Gaps in the literature on hydrogen sulphide toxicity, chosen for its relevance to the proposed study, were revealed by evaluation using the model.

The simplest relationship between exposure and outcome is the toxicologic or pharmacologic exposure (or dose) response curve, relating magnitude of exposure to magnitude of effect in a single tissue or organ system. In an intact organism, various effects, characterized by different toxicologic exposure:responses, occur simultaneously. As the outcome chosen must be measurable, the early phase of the toxicologic exposure: (or dose:) response curve is lost to observation to a variable degree, depending upon the limits of detection of the effect. Truncation of the organ-specific exposure:response relationships results in the familiar clinical 'step-ladder' pattern of threshold responses in the individual, but it is essential for purposes of risk assessment to appreciate that this pattern is as much an artifact of clinical observation or laboratory measurement as it is one of the aspects of the exposure:response relationship.

Translation of the toxicologic relationship into an epidemiologic exposure:frequency relationship is more than the aggregation of individual responses. Susceptibility of the subjects varies within the population at risk, usually in either a normal or bimodal distribution. The problem of biologic variation is usually treated as one of statistical 'noise' obscuring the 'signal', which is the relationship between the exposure and the response. It is more than that; it is a distribution of susceptibility characteristics that can be described and accounted for in the analysis and that reveal important aspects of the intrinsic mechanisms

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[1] Occupational Health Program, Faculty of Medicine, University of Alberta, Edmonton, AB

of defence, adaptation, and homeostasis, all of which influence the toxic effect.

Implications of increased attention to toxicologic models in the design of epidemiologic studies include:

1. Better characterization of individual risk factors;
2. Enhanced resolution of biologic effects as reflected in the analysis;
3. More efficient use of available data;
4. Improved generation of hypotheses; and
5. Insights into the distribution of susceptibility characteristics that may prove useful in both investigation and risk assessment.

1. INTRODUCTION

A major limitation on the design and interpretation of epidemiologic studies of toxic exposures has been the difficulty in accommodating, and indeed our frequent failure to recognize, the implicit biological assumptions that form the basis of our studies. Instead, we have adopted a simplistic working hypothesis that concentrates on relating clinical outcomes to exposure to the hazard, without rigorously examining the susceptibilty of the subject exposed and other important determinants of the response. In this discussion, we will examine some of these assumptions and construct a general model illustrated by the literature on hydrogen sulphide (H_2S) and other exposures of interest in petrochemical and hydrocarbon fuel technologies.

The vocabulary we will use is a hybrid of toxicology and epidemiology. In studies that examine health outcomes resulting from the effects of toxic substances or various forms of energy, it is customary to use the term exposure to describe the contact and interaction between the hazard and the exposed person. The term exposure can be applied to physical hazards, such as safety violations, but is more typically used, as in this discussion, for chemical or energy hazards, such as H_2S fugitive emissions or radiation from weld X-ray apparatus.

The effects so created may be immediate but those that are delayed are usually of greatest scientific interest because they are usually more complex and more challenging to detect. The selection of an appropriate outcome to study is a choice made largely on the basis of practical considerations: what is described in the literature and in folklore, what can be measured, and what is important in the prevention of injury. Rarely, the literature is sufficiently well-developed to permit the identification of a possibly significant outcome on a theoretical basis. A targeted search is seldom undertaken without some preliminary evidence suggesting that an outcome is likely, however. One important reason for this is that when numerous health outcomes are looked for in any large population, a few will be found on the basis of chance alone and the proper interpretation of the findings may therefore be inconclusive. Another reason is that research is expensive and practical results often difficult to demonstrate, so that it is more cost-effective to look for effects that are likely in populations where they are likely to be found, that is in the highest risk groups most often those exposed in their occupations. This logic also applies to the characterization of host factors, so that we are typically looking for interactions that may modify the outcome only after the existence of the outcome itself is well-established. This quite understandable situation of putting the horse firmly before the cart in our research strategy has two negative consequences. Since we seldom look at them except when they fail to protect and thus come to our attention, we know rather little concerning the important biological processes that keep most people quite healthy in the face of a continuous onslaught of minor toxic exposures from conception to death. Also, we rarely have the information we need to construct a plausible model for population effects in advance when we are designing a study.

A general model may have practical utility beyond scientific inspiration if it provides a robust framework in situations where too little is known to target specific host factors. For this reason we have given considerable thought to biological models incorporated into our thinking about exposure-related disorders.

2. BIOLOGICAL MODELS IN THE DESIGN OF EPIDEMIOLOGICAL STUDIES

Central to the interpretation of epidemiological studies are the assumptions that underline the measurement of outcomes and risk factors. When a strong basic research foundation is in place to provide a mechanistic model, as in the case of cardiovascular epidemiology, these assumptions can be refined to considerable sophistication. Population studies can be used to investigate specific aspects of the mechanism, such as the role of certain lipoproteins in atherogenesis. In occupational and environmental epidemiology, on the other hand, the mechanistic model is usually incomplete and the measurement of exposure is limited by practical difficulties. If we are to progress to a point that epidemiologic studies of exposure-related outcomes may have the same power to generate mechanistic hypotheses as those in cardiovascular epidemiology, we must first examine the implicit assumptions that form the basis for our biological models.

Investigators in infectious disease and chronic disease epidemiology have long appreciated the role of multiple factors in determining a health outcome. In the diseases they study, such as AIDS or hepatitis, and coronary artery disease, cancer, or arthritis, respectively, there is seldom a single factor implicated as the cause of any disease. Rather, there are etiologic agents that interact with host factors in a setting that may allow a disorder to develop and progress. The triad of susceptible host, agent, and environment is the essential paradigm of infectious disease investigation and works equally well applied to cardiovascular and other complex chronic disorders. Applied to occupational and environmental epidemiology, however, it has been more speculated upon than searched for. The reason for this relative neglect is primarily technical. A large degree of uncertainty in quantifying exposure is present in virtually all realistic exposure situations in the environment or in the workplace so that ambient assessment of the role of the agent of exposure is usually unclear and nearly always controversial. Also, characterization of host factors by laboratory or clinical investigation is extraordinarily difficult. Few model systems of host factors in toxic outcomes have been characterized in any detail, the most important being hydrocarbon hydroxylase activity, which affects the response to many polycyclic hydrocarbons, and paraoxanase activity which affects the response to organophosphate pesticides. For the rest, we usually refer to biological variation and simply treat host factors as a black box (Crammer 1974; Schmahl 1977; Selikoff 1980).

To move forward, however, perhaps we need to open the black boxes of mechanism and incorporate them into our thinking in study design. In particular, we need several well-characterized examples that will guide us in developing a generalizable model (Gehring et al. 1978). This absolutely requires an interdisciplinary approach combining the methods of toxicology and epidemiology. A multidisciplinary approach, in which toxicologists and epidemiologists attack the same problem in parallel but separately and interact only superficially, will not yield the needed results because it is the incorporation of principles of each into the other that is important.

The simplest relationship between exposure and outcome is the dose:response curve in toxicology and pharmacology. Here we are concerned with the magnitude of the response proportional to the amount of the agent given. In this relationship, a given amount of an active agent delivered is associated with a particular level of response in an individual subject or preparation. For example, varying the concentration of a smooth-muscle agonist in a saline bath surrounding a segment of the ileum of a guinea pig results in a proportional difference in contraction of the segment over a wide range of concentrations, from a threshold level below which no effect is detectable to a high level above which no additional contraction is possible. The magnitude of the response is measured by apparatus selected for a particular effect. The sensitivity of the measurement depends on the effect to be measured and the apparatus designed to measure it. Electrophysiologic measurements of calcium flux across the sarcolemma of a muscle fiber may well be sensitive to effects orders of magnitude below those demonstrable with a strain gauge that measures the force of contraction of the muscle. In toxicology, therefore, it is essential to select an effect that is both biologically meaningful and can be measured accurately. This problem of measurement removes a huge spectrum of biochemical, biophysical, and early physiological changes from consideration however interesting they may be otherwise.

The typical toxicological exposure:response relationship is illustrated by Figure 1. Here we use the term exposure because the total amount delivered is less important than the concentration in some medium, usually air or water. A given level of exposure produces a proportional magnitude in effect within a fixed range of sensitivity, described by a sigmoid curve in which initial changes produce increasing responses as exposure increases; an inflexion point is reached, and close to the maximal effect increasing exposure produces lessening effect until the maximum possible is achieved (Hammer et al. 1978; Hatch 1968; Litchfield and Wilcoxon 1949). This function is exceedingly simplistic, of course, because several muscle layers, for example, may be responding simultaneously but with different characteristics in different organs of an intact animal or in a single tissue preparation.

As a general principle, the toxicologic exposure:response relationship has been extremely robust, meaning that it explains a great deal and does not need to be much modified when we change our assumptions. It has limitations, however. In environmental health sciences, we speak of exposure rather than dose, as we might in pharmacology, because the organism is exposed to a concentration of the substance of interest in a medium and

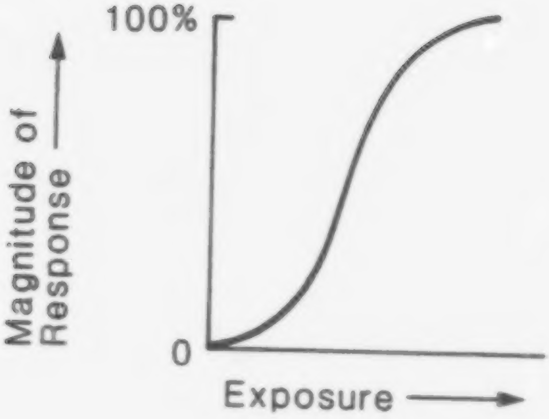

Figure 1. The toxicologic or pharmacologic exposure:response relationship.

this concentration varies over time, often rapidly, while in the exposure:response relationship in pharmacology a given mass is supposed to produce a given effect at one point in time. In many environmentally significant exposures, the rate of change of the concentration in the short-term may be a very important factor. It is often said that over a wide range of exposures inhaled agents tend to follow "Haber's Law:" the product of the concentration and the duration of exposure needed to achieve a given effect is approximately constant. This is the logic behind the familiar time-weighted average (TWA) in occupational hygiene. This assumption allows us to treat variations in exposure more simply by taking the average over time. Unfortunately, this is a very crude relationship that does not hold true for many exposures. Fatal exposures to H_2S in humans, for example, may take place at 150 ppm for 6 h (concentration - time product = 0.252) or 650 ppm for 8.5 min (0.005). The plot of fatal exposure to H_2S shows a sharply falling product with increasing concentration. This means that, for H_2S, higher concentrations are much more toxic, even with proportionally shorter exposure levels. In any realistic environmental exposure, the concentration changes rapidly, often while the effect is still developing in the target organ. Thus, the toxicological exposure:response relationship must be understood to be a very useful abstraction, not a precise description of events at the tissue level.

For any given exposure level, a variety of effects may be occurring simultaneously in different tissues of the intact organism, and even in different functions of the same organ. In Figure 2, a family of curves is presented to represent the responses of various target organs. For H_2S, curve A may represent the lung, B the heart, and C the central nervous system (CNS). For a solvent, A may represent the CNS, B the liver, and C the kidney. Each has its own characteristic exposure:response relationship. Whichever is most sensitive to the toxic effect will predominate in the clinical picture overall but often an effect will be unexpectedly prominent in an exposed individual because of prior exposures, age, or genetic or acquired susceptibility (Alvares 1978; Selikoff 1980; Vouk et al. 1980; Vesell 1979).

Returning to first principles, recall that the measurement of an effect depends on the outcome chosen to reflect that effect and the sensi-

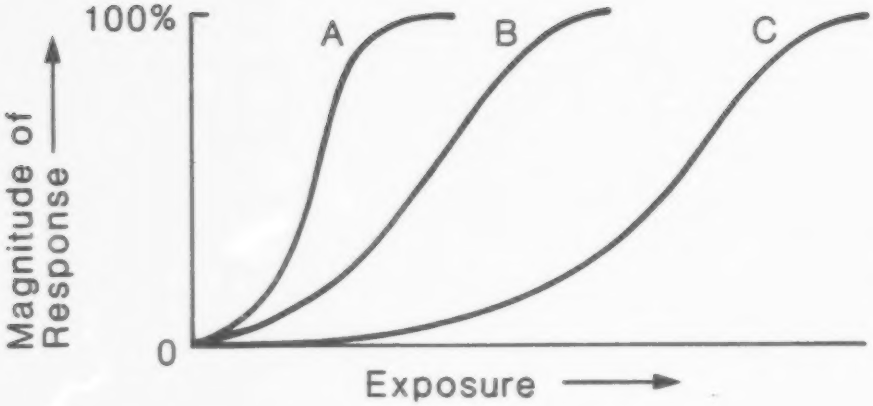

Figure 2. The toxicologic exposure:response relationship varies with the target organ being considered (A, B, or C).

tivity of the measurement. In studies of human beings, we usually apply measurements that have been originally developed to detect disease states or abnormalities that suggest the evolution of illness. These clinical measurements have marked limitations, as every clinician knows. It takes extensive injury to the kidneys before the usual blood tests for renal insufficiency become abnormal, for example. Human beings have a large reserve in the functional capacity of the liver, kidney, and lungs, especially. Thus, we can only detect clinical impairment in an exposed subject when the effect produced has advanced to a considerable degree, which may be different for each organ. Figure 3 suggests the large range of injury that may remain undetectable. In this example, A is the most sensitive target organ and also that for which available clinical tests are most sensitive, detecting an abnormality when the effect reaches E_A, the minimum detectable effect level for this organ system. Target organ B is more resistant but available clinical tests are also extremely insensitive, so that much more injury must have occurred before an effect is detectable at E_B. Target organ C is more resistant still but because clinical tests appropriate to its evaluation are more sensitive injury can be detected at an exposure only slightly higher than that for B (Crammer 1974; Selikoff 1980).

The result of this variability in target organ sensitivity and in detection levels of available clinical tests results in the truncation of the exposure:response relationship and the appearance of apparent thresholds, as in Figure 4. Thresholds are among the most controversial concepts in toxicology. A threshold is necessarily linked with a detectable effect. Exposures below a threshold are not necessarily innocuous. For example, our concept of lead toxicity has changed dramatically in recent years as more sensitive tests have been developed to evaluate target organs previously difficult to assess. The literature on H_2S is very weak in providing the information needed to construct exposure:response relationships of this type, but two effects that have been examined in this way are odour and conjunctivitis, or gas eye. In Figure 5, it is apparent that these two clinical effects of H_2S behave very differently indeed. The phenomenon of olfactory paralysis cuts short the exposure:response at high levels.

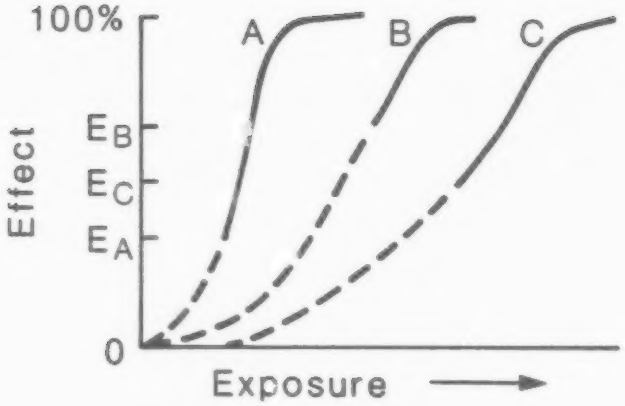

Figure 3. The limits for detection of an effect (E) varies with the tests employed for each target organ; below this threshold, changes are not detectable.

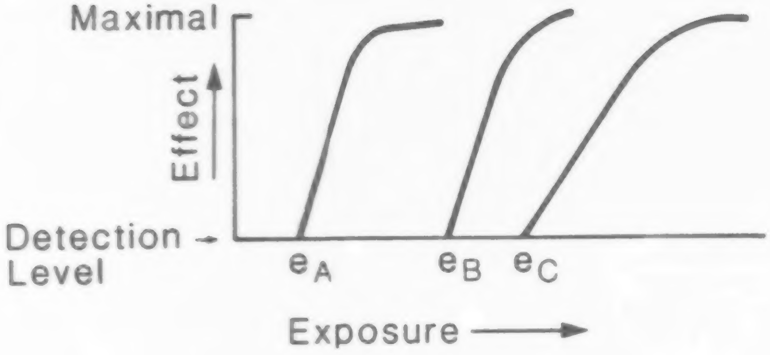

Figure 4. Threshold concentrations (e) are determined by the limits of detection for the effects sought.

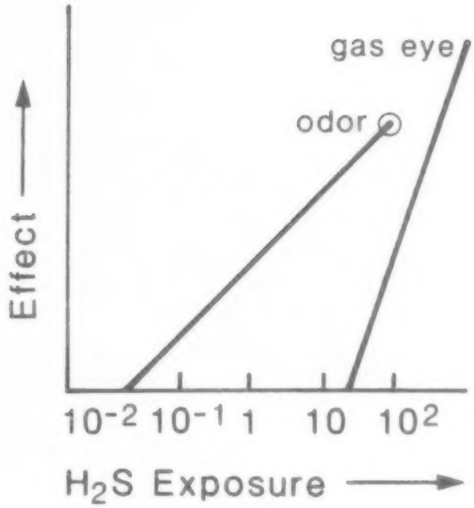

Figure 5. Hydrogen sulphide exposure:response curves are very different in slope and show very different thresholds depending on the effect observed.

Translation of the toxicological exposure:response relationship into an epidemiological exposure:frequency relationship is fundamentally dependent on these toxicological principles (Hatch 1968). We select an outcome only partly because it is significant in the evaluation of an environmental or occupational exposure. As important is our ability to measure the outcome, which leads inevitably to our over-emphasizing some effects and missing others. The most frequently used endpoint in occupational epidemiology is mortality, because death certificates are not difficult to obtain and are reasonably accurate for the purpose. (Death certificates are seldom in error for cancer but are often wrong for conditions such as heart disease.) Death is a rather extreme endpoint, however, fortunately uncommon in most disorders and rarely able to give a complete picture of trends for a population except for a few causes of death, such as lung cancer, which are usually fatal and for which effective treatment is changing only slowly.

The epidemiological exposure:frequency relationship builds on the toxicological exposure:response relationship by summing over the numbers of individuals in the population who demonstrate the detectable effect at a given exposure level. Figure 6 shows an idealized exposure:frequency relationship in which the cumulative percentage of individuals demonstrating the effect rises with the magnitude of exposure, again following a sigmoid curve. (In most real epidemiologic studies, exposure measurement is too crude and the number of individuals studied too small to yield a continuous curve.) The sigmoid shape of this curve is due to a different phenomenon than that of the toxicological relationship. Here a variation exists in the susceptibility of individuals in the population to the exposure. Most often, this biological variation can be described by the typical Gaussian normal curve (Figure 7) but sometimes, as in the case of genetic disorders, the distribution is bimodal (Figure 8). In the population, either way, there are some individuals who are highly susceptible and others who are highly resistant. We set occupational exposure standards to prevent injury or discomfort to the large majority of the population. We depend on the highly susceptible to know of their vulnerability and to exclude themselves from the response or to complain. Increasingly, we are instituting medical surveillance when appropriate to detect them before serious injury occurs

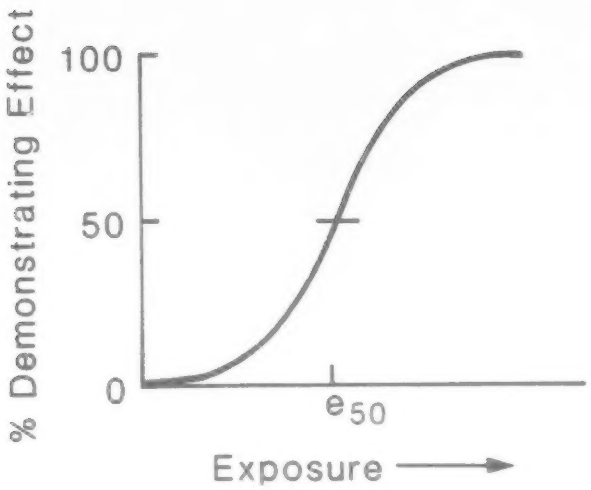

Figure 6. The epidemiologic exposure:frequency relationship counts the proportion of individual subjects showing the effect (e_{50} is the exposure level at which 50% of the subjects show the effect).

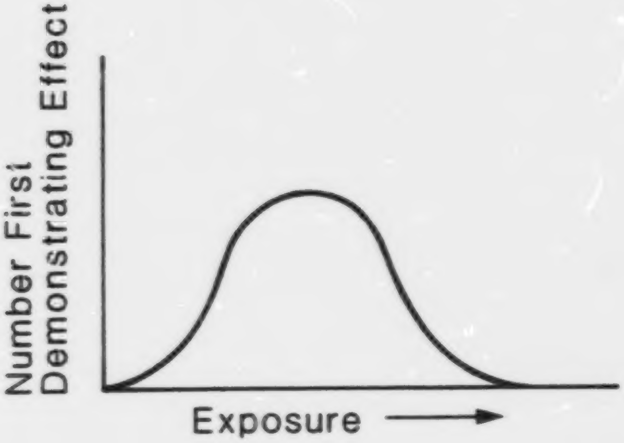

Figure 7. Susceptibility is usually distributed normally in a population as a result of biological variation among the subjects.

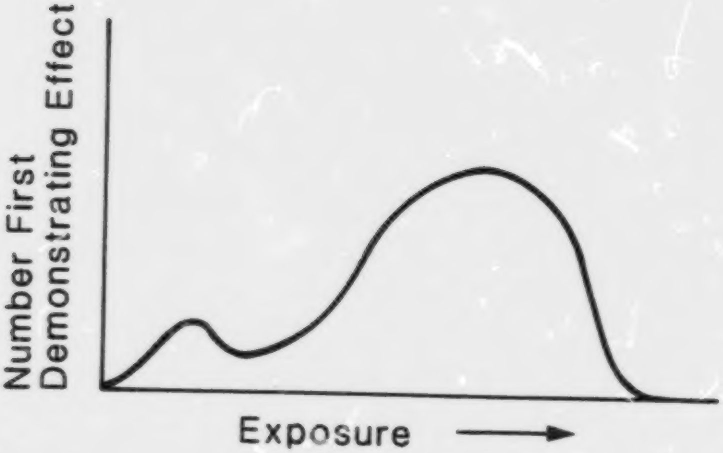

Figure 8. When some members of a population have a genetic or acquired condition that renders them more susceptible than the majority, susceptibility may be bimodal in distribution (e.g., asthmatics or persons with rare genetic disorders).

(Arlett and Lehmann 1978; Fraser et al. 1979; Guidotti 1985; Hatch 1968). (These same surveillance programs also identify persons who are exposed to unusually high levels.)

In epidemiology, the problem of biological variation is usually treated as one of statistical noise obscuring the signal, the signal being the demonstrable relationship between exposure and effect. Yet, the mechanisms of biological variation are fundamental to understanding exposure-related outcomes because it is these mechanisms that oppose the action of the toxic insult. Figure 9 shows this schematically. In the case of H_2S, for example, the effect of exposure would be much worse and longer-lasting at low levels if elaborate biochemical and physiological mechanisms did not exist to remove, metabolize, counteract, and adapt to H_2S exposure; for H_2S, these mechanisms include bonding to metalloproteins, oxidation to sulphate, increased ventilation, and the limited development of tolerance to low levels, respectively, the latter playing a much more important role in other exposures such as oxidant gases. These mechanisms are basic to the toxicologic response but are seldom investigated by epidemiological means because to do so first requires the identification of a mechanism accessible for measurement in humans. Yet, the distribution of such host factors in a population may be at least as important as the level of exposure (within a given range) in determining the number of individuals affected (Beauchamp et al. 1984; Harris et al. 1986; Mitchell et al. 1986; U.S. National Research Council 1979).

3. EXPOSURE MODELS IN THE DESIGN OF EPIDEMIOLOGICAL STUDIES

Further complicating the translation of the toxicological exposure:response relationship into an epidemiological exposure:frequency relationship is uncertainty in the estimation of individual exposure.

The considerations of sensitivity, accuracy, and precision common to all measurement techniques apply to exposure quantification as well as to clinical tests. As a practical matter, the technology for measuring exposures directly is not a limiting factor for most occupational applications. Rather, the difficulty lies in estimating exposure for each individual included in the population of interest. Individual exposure measurements over time are rarely available, except among workers exposed to

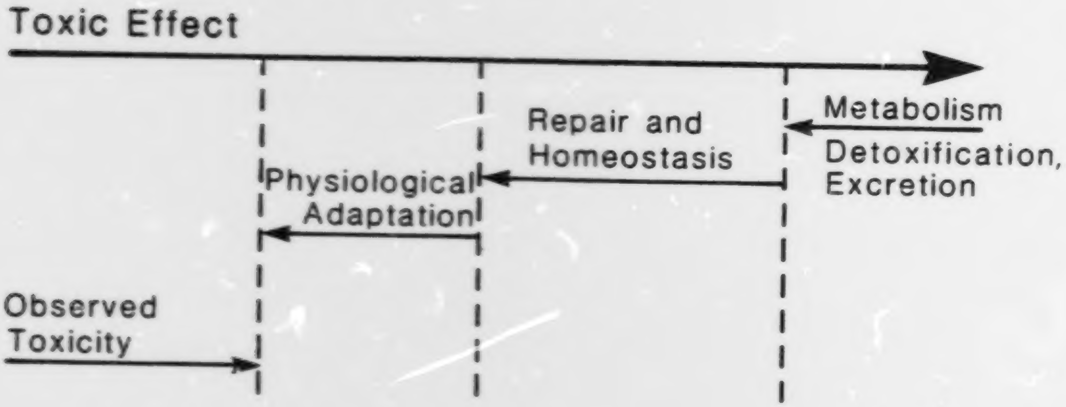
Toxic Effect
Metabolism
Detoxification, Excretion
Repair and Homeostasis
Physiological Adaptation
Observed Toxicity

Figure 9. The potential toxic effect of an exposure is reduced by many mechanisms in the body that are called collectively 'host defences.'

radiation. Instead, our best estimates come from sampling individual exposures among the job classifications and in work stations identified. This is seldom performed systematically except in the most elaborate prospective studies or when exposure estimates for an historical cohort must be reconstructed by duplicating the job exposures after the fact. More commonly, only area measurements are available. Most commonly, there are no exposure data at all, or records so fragmentary that they can be used only to establish a probable range.

Occupational hygienists are the professional experts in measuring exposure, as in so many other essential occupational health functions. A huge literature of area exposure monitoring data has been accumulated by these professionals for a variety of industries using appropriate technology. While individual circumstances differ and a variety of factors may distort the pattern, some generalizations can be made on theoretical grounds that fit the empirical data reasonably well. Where hazardous exposures exist, they are contained, controlled, or contact with them is limited by personal protection of workers up close. Thus, exposure right at the source of a fugitive emission is unlikely except in unusual accidents. As an emission escapes, it is subject to dilution in the medium (usually air) within the space of the plant or operation. Air currents will accelerate mixing; physical obstacles to diffusion will delay it. A single release diffuses into the volume of the plant but a continuous release will fall in concentration, all other factors being equal, by at least the inverse square of the distance from the source. If indoors or if the agent is heavier than air, like H_2S, this logarithmic decay in concentration will be followed more closely than outdoors, where the height of diffusion is not restricted or if the agent rises. Thus, the idealized curve for the probability that a given individual has been exposed in a realistic workplace setting is roughly that in Figure 10. Virtually no one within the plant boundary has no exposure whatsoever, however minimal, to a volatile agent but only a few sustain very high exposures. In a workplace with a random distribution of workers on the shop floor or of the time spent at dispersed locations by workers and a single point source of fugitive emissions, a larger number will predictably sustain low exposures. The shape of the curve approaches a log-normal distribution because as the distance from the source increases the concen-

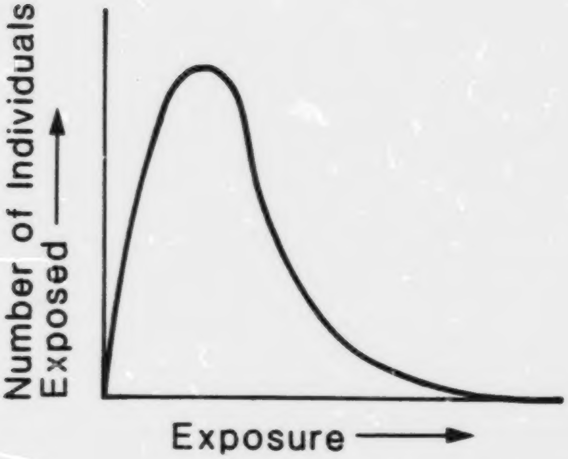

Figure 10. The opportunity for exposure in the workplace in realistic situations is usually skewed; most subjects are exposed to lower levels and few to high levels.

tration falls but the number potentially exposed rises. Obviously, few workplaces have uniform or random distributions of workers in relation to a single source, but in operations where workers move around from site to site frequently, as in a gas plant, and the most hazardous operations are contained and monitored, this model may not be a bad first approximation.

Accidents may result in a small number of workers sustaining much higher exposures for short periods, of course. Where the toxicity of the agent is cumulative, as in lead, the additional exposure must be compared to the much longer opportunity to absorb the reagent at low levels. Unless massive, the time-weighted exposure may still be relatively modest. Very high accidental exposures, sufficient in themselves to produce toxic effects, are not common and are subject to the general principle in safety that the probability of an accident occurring is inversely proportional to its severity, in large part because that is precisely how we design things. When a short-term high level exposure occurs it is likely to be qualitatively different in its effects from usual occupational exposures, as suggested earlier by the discussion of the limitations of Haber's poorly termed Law. Hydrogen sulphide-induced knockdowns result from this type of accident.

Since the majority of individuals in an exposed population is likely to be exposed at lower levels and only a fraction of the population is likely to be susceptible to the effects we are capable of measuring, only a few individuals are ever likely to show major effects (Figure 11). The experience of these few is likely to be diluted by aggregation with the much larger majority at reduced risk. The net effect of these factors is to reduce our estimates of risk. Also, the results predictably tell us little about things we need to know: what the exposure experience of those experiencing an effect might have been and what host factors protect the majority. They only tell us how common the apparent problem may be in a given plant or industry, within the limits of our measurement techniques.

Exposure modelling is a fundamental problem in epidemiologic studies of this type and one addressed vigorously by our occupational hygiene colleagues. We need to be much cleverer in using these models to estimate individual exposure and in applying them to yield estimates of error in our studies.

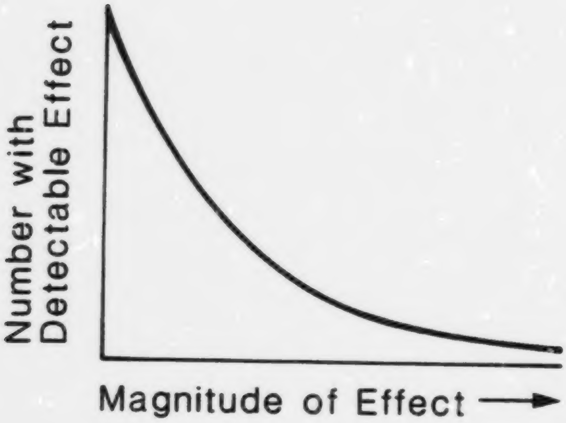

Figure 11. In realistic exposure situations, few subjects usually show serious effects and most show modest or no detectable effects.

4. DISEASE OUTCOMES OF INTEREST IN A STUDY OF HYDROGEN SULPHIDE EXPOSURE

In this section, we will consider disease outcomes that might be considered in an occupational health study of exposure to H_2S. This is intended to be an illustrative exercise and not to imply that such outcomes are at all likely in the oil and gas industry. The emphasis here is on the possible, not on the probable.

The disease outcomes that might plausibly be searched for in a study of occupational exposure to H_2S must be selected from the available human data and a highly variable,dated, and incomplete animal literature. We will not here address the problem of other exposures common in the sour gas industry but they are many (Table 1) and could conceivably contribute to any observed toxicity. They would certainly have to be taken into account in any rigorous study.

The toxicity of H_2S has been reviewed on numerous occasions and we will not duplicate these sources here. Rather, we will emphasize target organic systems of principal concern requiring investigation (Beauchamp et al. 1984; U.S. National Research Council 1979).

Hydrogen sulphide interacts with a number of enzymes and other macromolecules, including hemoglobin and myoglobin, a property to be expected because most macromolecules are held together by disulphide bonds prone to disruption by aqueous sulphide. The critical target enzyme of H_2S is cytochrome oxidase, actually a family of related enzymes constituting the electron transport system in oxidative phosphorylation, the principal energy-generating system of the cell. Oxygen is the final substrate of this system and is necessary to its function, so that the effect of H_2S in disrupting cytochrome oxidase activity is the same as oxygen deprivation or asphyxiation except that it may act more quickly. This effect of H_2S, which it shares in common with other agents, is called cellular anoxia. Because the cytochrome oxidase system is common to all mammalian cells, the acute toxicity of H_2S roughly parallels the oxygen requirements of the target organ in question; this is one possible explanation for the prominence of the central nervous system and the heart in the toxicity profile.

Another property of H_2S is its irritant effect on mucous membranes. This property acts on exposed surfaces of the body and adds the

Table 1. Principal exposures in the sour gas industry.

Hydrogen sulphide
Mercaptans
Carboxyl sulphide
Hydrocarbons (C1 to C5)
Solvents
Amines[a]
Elemental sulphur

[a] Principally monoethanolamine and diethanolamine.

respiratory tract and the eye to the principal target organs, which are of course also vulnerable because of their unprotected contact with the gas in air. Hydrogen sulphide penetrates deeply into the respiratory tract because its solubility is relatively low, rendering it capable of causing pulmonary edema acutely due to alveolar injury.

Other properties of H_2S are difficult to assess because these two predominate. It is possible that the acute central nervous system effects of H_2S observed in a knockdown or the arrhythmias observed after exposure represent a primary effect of the agent on the brain or myocardium (Haider and Hasan 1984; Kosmider et al. 1966), respectively, but they are as likely due to the anoxic effect (Graham 1977). The implications are very great, since a primary anesthetic action of H_2S, similar to that of many lipid-soluble small-molecular weight compounds, is likely to be reversible whereas anoxic brain injury frequently leads to long-term sequelae (Graham 1977).

Table 2 presents the chronic health outcomes of chief concern plausibly associated with exposure to H_2S at levels encountered in occupational exposures. The outcomes are not necessarily demonstrated in the literature but would be suggested by the literature and local experience as among those to which attention should logically be directed. The list is arranged in diminishing order of the strength of evidence for any effect involving the organ system, with that for hemotologic changes judged weakest. Selection of outcomes for incorporation into a study should not be restricted by this list, however, because a variety of conditions may have uses as markers of exposure (e.g., dermatoses in many exposures) or may, as in the case of cancer on the list, have been inadequately evaluated. Clearly, however, central nervous system, respiratory, cardiac, eye, and host defence lesions emerge as the abnormalities to be sought after.

The central nervous system presents a particular problem in the evaluation of chronic health outcomes. Lesions affecting it might represent primary effects of H_2S, secondary effects from low-level cellular anoxia, or the sequelae of acute brain injury sustained during a knockdown, which itself in any individual case could represent an episode of toxic, anoxic, or even traumatic injury, the latter occurring if the subject struck his head in the fall. For this reason, subjects recovered from knockdowns should probably be studied separately from cases of chronic low-level exposure,

Table 2. Chronic health outcomes of concern, plausible at levels of exposure ≤100 ppm H_2S in humans (Arnold et al. 1985; Beauchamp et al. 1984; U.S. National Research Council 1979).

Organ System	Evidence for an Effect[a]			Chronic Disease Outcomes of Interest
	Animal	Human	Human-Alta	
Central nervous	A, ?C	A, ?C	A, ?C	Dementia, cognitive dysfunction, affective disorders, cerebrovascular disease
Respiratory	A	A	A	Chronic obstructive airways disease, asthma, lung cancer
Heart	A	A	A	Coronary artery disease, sudden death, arrhythmias
Eye	A	A	A	Chronic keratoconjunctivitis, cataracts, retinal disorders
Host defenses*	A	0	0	Infections, immune disorders, arthritis
Hepatic**	(A)	0	(A)	Hepatic dysfunction-marginal (Cirrhosis, hepatitis unlikely)
Reproductive	?A (A, in vitro)	0	0	Infertility, fetal loss, teratogenicity
Renal	?A	0	0	Renal insufficiency
Endocrine	A	0	0	Thyroid abnormalities
Cancer	(***)	0	0	All types
Hematologic	-	0	0	(None obvious)

[a] A = Evidence for acute effects
?C = Suggestive evidence for chronic effects, not confirmed
0 = No evidence available
- = Data available suggest no detectable effect
* = Host defenses include reticuloendothelial function, mechanical host defenses of respiratory tract, cellular immune function, and humoral immune function
** = Congestive hepatic lesion was described at necropsy(in an Alberta case[24]) that probably represents passive congestion due to cardiac failure. Animal studies refer to biliary function, not hepatocellular injury.
*** = Sulphide salts reported to be mutagenic in vivo; no acceptable animal exposure study has been reported

although the lifetime average exposure level such a subject has sustained might not be exceptional.

Having identified an organ system in which an effect is possible, the next question is how this effect is likely to manifest itself. The available animal evidence points to injury to the cerebral cortex, cerebellum, and possibly the brainstem and spinal cord at concentrations approaching those that humans might encounter (Haider and Hasan 1984; Kosmider et al. 1966; Savolainen 1982; Savolainen et al. 1980). The lesions are similar to those seen in oxygen deficiency and in poisoning by other cytochrome oxidase inhibitors (Graham 1977; Savolainen 1982). The pattern of injury suggests that changes in the way the subject thinks and feels emotionally are more likely to appear than clinical findings that can be detected in a physical examination. Sophisticated tests of cortical function are difficult to perform and to standardize; tests of brain electrical activity must be done in a hospital or special laboratory and paper and pencil tests are often difficult to interpret objectively and quantitatively (Ptovin and Tourtellote 1985). Thus, it is difficult to evaluate higher mental functions in an epidemiological study and the tests available are not sensitive. This means that in the model of exposure-related illness described, our E for cortical injury will be very high and a negative result of such a study will not be convincing because it could easily have missed some affected subjects. Relying on a physician to detect evidence of organic brain disease would be even less sensitive because the brain is a tough organ with a great deal of reserve. It must be fairly severely damaged at the cortical level for an abnormality to be noticed by someone unfamiliar with the subject. There may be a new test available to us soon that will make such a study practical but the problems should be apparent using the present situation as an illustration. Any apparent threshold for brain injury would be suspect because the detection would be too insensitive; any negative findings would be equally suspect. There would always be concern that something important was overlooked.

One way to overcome this problem is to design the study using the most sensitive possible tests. Sometimes tests are so sensitive that the results reflect normal variations of the body and are meaningless, so one can go too far. Another is to use cleverer study designs, such as nested case-control or exposure-generated case-control studies to pin down the characteristics of those individuals more precisely. Sometimes, however, the most sensible approach is not to pretend that the entire population can be adequately evaluated and to concentrate on the extreme cases that at least suggest whether a problem exists or not.

5. CONCLUSION

Investigation of exposure-related disorders is a much more complex problem than detecting a clinical response in an exposed population. In this discussion, we have attempted to put the problem into context using hydrogen sulphide exposure as an example. It is not an ideal example, in many ways, but illustrates the issues well enough and is sufficiently familiar to be meaningful. The evidence to date leads us to two firm conclusions, however:

1. Hydrogen sulphide, in general, is not good for you; and
2. Further study is needed.

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DO AIRBORNE POLLUTANTS AFFECT ANIMAL HEALTH?

by

M.G. Prior[1] and R.W. Coppock[1]

ABSTRACT

Acid-forming pollutants, such as the oxides of sulphur and nitrogen, do not occur as the sole chemical compound, or solute, in the ambient air, or solvent. Rather, they occur in combination with other pollutants. This fact influences their effects on animals, for the sum of the effects of exposure to these pollutants may be additive, synergistic, or subtractive to their individual effects. Furthermore, the presence of naturally occurring gases, such as ozone, may alter the toxicity of a particular pollutant. This paper focuses on sulphur-containing pollutants and their possible effects on animal health with particular reference to hdyrogen sulphide, carbon disulphide, carbonyl sulphide, mercaptans, methyl sulphide, diethyl sulphide, sulphur dioxide, and sulphur. Sulphur compounds may be present as gases, particles, or aerosols. In these forms they might be predicted to have health effects, especially on the respiratory tract, skin, and eyes. If any effects occur in livestock, these are possibly the result of the simultaneous exposure to one or more sulphur compounds, together with a variety of non-sulphur compounds. The latter include ozone, ammonia, and the nitrogen oxides. The effects induced by airborne pollutants must occur either in large enough numbers, or with sufficient severity, to allow their unequivocal identification and separation from the normal and expected biological values and events.

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[1] Alberta Environmental Centre, Vegreville, AB.

1. INTRODUCTION

Airborne pollutants are a highly diverse group of substances consisting of particles, aerosols, vapours, and gases of inorganic and organic substances. Examples of particulate air pollution observed in farming operations are soil and grain dusts. Aerosol pollutants associated with farming are the water droplets and pesticide mists seen during spraying operations. Vapours are gases of volatile substances such as motor fuels and paint solvents. Gases are substances such as propane. Airborne pollutants enter the body through the respiratory tract. Deposition of particles in the respiratory tract depends on particle size. Generally, particles with a diameter between 30 to 5 µm are deposited in the nasopharyngeal region, particles with a diameter of 5 to 1 µm lodge in the trachea, bronchi, or bronchioles, whilst particles of less than 1 µm in diameter pass to the alveoli.

Acid-forming pollutants, such as the oxides of sulphur and nitrogen, do not occur as the sole chemical compound, or solute, in the ambient air, or solvent. Rather, they occur in combination with other pollutants. This fact influences their effects on animals, for the sum of the effects of exposure to these pollutants may be additive, synergistic, or subtractive to their individual effects. Furthermore, the presence of naturally occurring gases, such as ozone, may alter the toxicity of a particular pollutant.

This paper focuses on sulphur-containing pollutants and their possible effects on animal health. Sulphur compounds may be present as gases, particles, or aerosols. In these forms, they might be predicted to have health effects, especially on the respiratory tract, skin, and eyes. People in a number of agricultural communities in Alberta close to sulphur extraction gas plants, and who have been personally affected by emissions, demonstrate a high level of concern for the effects of gas plant pollution (Environment Conservation Authority 1973). Well blowouts may release hydrogen sulphide and other toxic substances into the atmosphere as happened, for example, in the Camrose area in 1973 and the Drayton Valley-Lodgepole area in 1977 and again in 1982 (Energy Resources Conservation Board 1978; Lodgepole Blowout Inquiry 1984; New Norway Scientific Committee 1974). The last example was the most extensive; the highest concentration recorded away from the blowout site was 23 ppm at a location 13 km southeast of the blowout site, the maximum concentration at two towns 20 km to the east and northeast was 14.5 ppm, and the maximum concentration at Edmonton, some 140 km to the east-northeast, was 0.5 ppm (Lodgepole Blowout Inquiry 1984). This concern has shifted to include the perception that a number of as yet unspecified health effects may be due to, or exacerbated by, sulphur-containing emissions. These concerns are not limited to livestock but also include wildlife and human health.

2. SOUR GAS

Sour gas is a colloquial term for natural gas that contains varying concentrations of hydrogen sulphide (H_2S). Natural gas is a complex mixture of aliphatic, alicyclic, and aromatic hydrocarbons and, in the case of sour gas, compounds containing sulphur. Predominant hydrocarbons are generally low molecular weight aliphatics such as methane, ethane, and butane. Alicyclic and aromatic hydrocarbons are found predominantly in the condensate fraction. Gaseous and volatile sulphur compounds found include hydrogen sulphide, carbonyl sulphide, carbon disulphide, and methyl-, ethyl-, and propylmercaptans. Generally, H_2S is the major sulphur-containing constituent. The chemical composition of sour gas varies between natural gas deposits. Some sour gas wells contain only low levels of H_2S, whilst other wells, drilled for the commercial value of sulphur, contain H_2S as the predominant gas. The recovery and processing of sour gas may give rise to sulphur dusts and to oxidation products such as the sulphur oxides.

The sources of these sulphur-containing and acid-forming emissions are fourfold:

1. Emissions from normal industrial operations;
2. Emissions from malfunctioning industrial operations;
3. Catastrophic events, for example, well blowouts; and
4. Natural sources, for example, sulphur springs or anaerobic decay of biological materials.

The particular constituents present in emissions from each of these sources will differ, and often vary between sources in the same category.

Unlike many airborne pollutants, sulphur and its compounds occur naturally. It should be noted that sulphur is essential for plant and animal life and is present in vital tissues (National Research Council of Canada 1977).

2.1 INVESTIGATIONAL APPROACHES

The potential animal health effects of acid-forming pollutants may be studied in three ways:

1. Epidemiological studies of general or selected animal populations exposed to these pollutants in ambient air;
2. Studies on farm animals accidentally or geographically exposed to acid-forming emissions, sulphur gases, and volatile sulphur compounds; and
3. Laboratory experiments on experimental laboratory animals and livestock.

Each approach provides a different set of information which is not easily transferred from one category to another.

The study of chronic conditions in a general population exposed to airborne pollutants rarely shows an unequivocal cause-and-effect relation. There are criteria by which the likelihood that the relation is one of cause-and-effect can be judged. These have been elaborated by Hill (1965) and may be summarized briefly:

1. The strength of the association as indicated by the relative incidence of the condition(s) under study in the compared population;
2. The consistency of the finding;
3. The association should be specific to particular population groups and types of disease;
4. The suspected cause should be observed to act on the population before the change in health status occurred;
5. A dose:response curve should be observed;
6. The association should be biologically plausible;
7. The evidence should be coherent and not conflict with other known facts about the natural history of the disease; and
8. Experimental evidence may be used to support epidemiological findings.

This information can be obtained from a number of sources such as production records, changes in body functions and behaviour, clinical observations, herd history, changes in clinical chemistry, or changes in pharmacokinetics. Although it is rare for all these conditions to be fulfilled, the more that are met, the more likelihood it is that the observed association is one of cause-and-effect (Hill 1965), and the more credible are the scientific findings.

It is important that routine common diseases which occur concurrently with exposure be differentiated from the effects of such exposure to sulphur-containing emissions. Not all events occurring in livestock during or subsequent to such exposures are necessarily caused by the constituents of the emissions. It may be difficult to accomplish this differentiation.

3. TOXICITY OF SULPHUR-CONTAINING COMPOUNDS IN SOUR GAS

3.1 HYDROGEN SULPHIDE

Hydrogen sulphide is a colourless gas having the characteristic odour at low concentrations of rotten eggs. The gas occurs naturally in coal, natural gas, oil, volcanic gases, and sulphur springs and lakes, and is a product of the anaerobic decomposition of sulphur-containing organic matter, such as manure pits. Also, it is a by-product of the production of coke, manufacture of gases from coal, production of viscose rayon, the kraft process of producing chemical pulp from wood, and desulphurization of sour natural gas. The occupational hazards of exposure to H_2S are well known (National Research Council of Canada 1981). The majority of environmental, as opposed to industrial, exposures are to H_2S together with other sulphur-containing compounds.

The results of experimental exposure of livestock and laboratory rats to H_2S are summarized in Table 1. In Alberta, the two major sources of exposure for livestock are manure gas and sour gas operations. Deaths have been reported in pigs and cattle following the emptying of slurry (manure) tanks when agitation releases the toxic gases (Clarke and Clarke 1975; Lawson and McAllister 1966; McAllister and McQuitty 1965).

Table 1. Effects of exposure of livestock and laboratory rats to H_2S under experimental conditions.

Species	Concentration (ppm)[a]	Exposure Time[b]	Effects	Reference
Goats: 3 to 4 yr, non-lactating females	10	4 d	Little evidence of discomfort or alteration in physiological parameters.	Hayes 1972 Hayes et al. 1972
	50	4 d	Stress, feed, and water intake to half-normal levels; lacrimation, shivering, reduced urinary output.	
	100	4 d	Slight reduction in respiratory rate, transient conjunctivitis, shivering, reduced urinary output.	
Cattle: mature dairy cows	20	21 d	Slight lacrimation, no change in milk production.	Hayes 1972 Hayes et al. 1972
	20 to 50	21 d	Discomfort and alteration in normal body functions.	
calves	20	7 d	Distress, lethargy, restlessness, occasional diarrhoea, and vomiting; coughing, irregular respirations and dyspnoea; photophobia, keratitis, corneal opacity, nasal irritation, and epistaxis.	Nordstrum 1975 Nordstrum and McQuitty 1976
	150	7 d	Severe keratoconjunctivitis, clinical blindness, reduced feed and water intake, elevated rectal temperature, lethargy, occasional diarrhoea and vomiting, coughing, irregular respiration, and dyspnoea.	
Pigs: 13 to 21 kg	12	7 to 19 d	Little effect.	Curtis et al. 1974, 1975
Rats:	10, 30, 80	90 d	No significant findings.	CIIT/Toxigenics 1983a, 1983b

[a] ppm = parts per million
[b] d = day

3.2 CARBON DISULPHIDE

Carbon disulphide (CS_2) is a colourless, volatile liquid with a sweet aromatic odour reminiscent of chloroform. The technical product is a yellowish liquid with a disagreeable odour of decaying radishes (World Health Organization 1979). Sources are viscose rayon manufacture, coal gas formation, industrial solvent, and sour gas (Coppock et al. 1981). Carbon disulphide evaporates at room temperature, and its vapours are 2.62 times heavier than air. In dogs, cats, and rats, CS_2 inhaled at concentrations between 32 to 3210 ppm induces excitement followed by drowsiness associated with tremors and ataxia, loss of conditioned reflexes, and altered disposition after prolonged exposure (Alpers and Lewey 1940; Dietzmann and Laass 1977; Ferraro et al. 1941; Lewey et al. 1941). Peripheral nerve degeneration, especially the branchial plexuses and sciatic nerves, has been observed in the dog and rat (Haltia and Linnoila 1978a, 1978b). Increased thickness of the aortic wall was observed in rats following prolonged exposure (Grodetskaya et al. 1979). Carbon disulphide appears to have an enhancing effect on atherogenesis induced by cholestrol in rabbits and rats (Wronska-Nofer et al. 1978, 1980). Altered endocrine function has been reported in female rats exposed to relatively low concentrations of CS_2, with increased thyroid activity and altered oestrus cycles (Kramarenko et al. 1969). Chronic interstitial nephritis has been described in rabbits following prolonged inhalation exposure (Cohen et al. 1959; Cuccurullo et al. 1978). Carbon disulphide is metabolised to carbonyl sulphide and sulphur radical by hepatic cytochrome P-450 and associated microsomal monooxygenase enzymes (DeMatteis and Seawright 1975).

3.3 CARBONYL SULPHIDE

Carbonyl sulphide is a pungent, colourless gas. It is a by-product of the oxidative metabolism of CS_2 (Daivi et al. 1975), and is apparently metabolized by hepatic carbonic anhydrase (Chengelis and Neal 1980). Rats, rabbits, and cats exposed to concentrations greater than 500 ppm of carbonyl sulphide developed convulsions, dyspnoea, loss of equilibrium, and respiratory failure. Pulmonary oedema was observed in some of the rabbits (Thiess et al. 1968).

3.4 MERCAPTANS

3.4.1 Methylmercaptan (Methanethiol)

Methylmercaptan is a colourless gas with an odour of decaying cabbage and is highly flammable. It is found in some natural gas deposits and in coal tar, is recovered from various petroleum distillates, and occurs in small quantities in vegetables such as garlic and onion. It is found in cabbage following microbial degradation of methionine and L-homomethionine. Methylmercaptan evolves toxic fumes when exposed to heat and fire. It quickly oxidizes to sulphur oxides, but also reacts with water, steam, and acids to form toxic flammable vapours. In rats, mice, and primates, it depresses the central nervous system, causes alveolar haemorrhaging, and muscular weakness. Rats and mice exposed to 50 ppm for 90 d demonstrated haematological changes and minor lung and brain effects. Biologically, methylmercaptan is a normal intermediate in the metabolism of sulphur-containing amino acids, and is used in the synthesis of new methionine and hence protein (Sandage 1961; Sandmeyer 1981).

3.4.2 Ethylmercaptan (Ethanethiol)

Ethylmercaptan is a colourless, highly flammable liquid, with a penetrating garlic-like odour. It occurs in natural gas, petroleum distillates, and coal tar, as well as in vegetables such as cabbage. Because it exists as a liquid at lower temperatures and as a gas at higher temperatures, all routes of exposure should be considered. In rats and rabbits, it is an irritant at concentrations greater than 500 ppm, depresses the central nervous system, and may cause muscular weakness, cardiovascular disorders, and changes in light adaption and in the haematopoietic system (Sandmeyer 1981).

3.4.3 Propylmercaptan (Propanethiol)

Propylmercaptan is a clear liquid with a very unpleasant odour. It is of relatively low toxicity (Sandmeyer 1981).

3.5 METHYL SULPHIDE (DIMETHYL SULPHIDE)

Methyl sulphide is a colourless liquid with a disagreeable odour and occurs in small quantities with methylmercaptan in gas. Larger quantities inhibit carbonic anhydrase. The oral LD_{50} in the rat is 535 $mg \cdot kg^{-1}$ (Braker and Mossman 1971; Sandmeyer 1981).

3.6 ETHYL SULPHIDE (DIETHYL SULPHIDE)

Ethyl sulphide is a liquid with a garlic-like odour. It occurs in trace amounts in petroleum deposits and may impair respiration and irritate the eyes (Selyuzhitskii 1972).

3.7 SULPHUR DIOXIDE

Sulphur dioxide (SO_2) is an oxidation product of H_2S and can be oxidized in the air to form sulphuric acid and sulphates. Sulphur dioxide and sulphur trioxide are the two sulphur oxides of greatest concern. The major pollution events in the Meuse Valley, Belgium in 1930, and in London, England in the winter of 1952 to 1953, caused by meteorological inversions, and the major contributor to the health effects in livestock and human beings, was believed to be SO_2. Respiratory distress was relieved in affected cattle by removal to unaffected areas or with oxygen therapy. Deaths in cattle in the London episode were attributed to a combination of SO_2, sulphuric acid mist, and other toxic agents (Anon. 1953; Cullumbine et al. 1954; Firket 1931, 1936).

Young pigs, exposed experimentally to 5, 10, 20, or 40 ppm SO_2 for 8 h, developed slight eye irritation, nasal secretion, salivation, and altered respiration at higher concentrations. Haemorrhage and emphysema occurred at the 40 ppm concentration. At 158 d post-exposure, pulmonary fibrosis was found in pigs exposed to 20 and 40 ppm (O'Donaghue and Graesser 1962). No significant changes in milk production, body weight, digestibility of the rations, palatability, or urine pH were observed in a 90-d feeding trial of cows fed a ration of mixed grain, corn silage, and either uncontaminated or contaminated (from SO_2 emissions into the atmosphere from an industrial plant) alfalfa hay (Cunningham et al. 1937).

3.8 SULPHUR

The feeding of 30 g of sulphur daily to cattle had no observable adverse effects (Clarke and Clarke 1975). In a recently completed trial at the Alberta Environmental Centre, cattle were fed normal and high but realistic levels of dietary sulphur. Both groups showed similar trends in biochemical parameters, feed consumption, and weight gain (Khan, personal communication).

4. RELATIVE TOXICITY OF THE CONSTITUENT COMPOUNDS

The relative toxicity of some of the compounds that might occur during the recovery and processing of sour natural gas deposits is listed in Table 2. The current standards for exposure of human beings to some of these compounds are summarized in Table 3. It should be noted that these values are based on an 8-h exposure period or normal industrial working day. There are no equivalent values for livestock.

The effects of simultaneous inhalation exposure of laboratory rats and rabbits to H_2S and CS_2 are summarized in Table 4. Again, it is noted that there is no similar information for livestock. However, there is some information on the effects on laboratory animals, livestock, and poultry to exposure to H_2S concurrently with different airborne pollutants, such as ammonia, CO_2, or SO_2, or other compounds such as ethanol. This is summarized in Table 5.

The information in Tables 2, 4, and 5 summarizes the available literature and indicates there are areas for which additional data would be helpful.

5. REVIEW OF FIELD DATA

Published reports of the effects of emissions on livestock are summarized in Table 6. It must be stressed that these observations represent the sum of the individual effects of all the airborne pollutants to which the animals were exposed. These pollutants include both sulphur- and non-sulphur-containing compounds. It is difficult if not impossible to replicate such complex mixtures under the more controlled laboratory or field conditions.

A study was conducted in west-central Alberta on two dairy and two beef farms. Analysis of forage, feed, and grain samples indicated that, in

Table 2. Summary of lethality of constituent chemical compounds found in sour gas; exposure is by inhalation route (Registry of Toxic Effects of Chemical Substances 1985; Tansy et al. 1981).

Compound	Species	Lethality[a]
Hydrogen sulphide	Rat	LC_{50} - 444 ppm·4 h^{-1}
Carbon disulphide	Rat	TCLo - 200 mg·m^{-3}·24h^{-1}
	Man	LCLo - 4000 ppm·30 mo^{-1} (est.)
Carbonyl sulphide	Rat	LCLo - 1400 ppm·75 mo^{-1}
Methanethiol	Rat	LC_{50} - 675 ppm
Ethanethiol	Rat	LC_{50} - 4420 ppm·4 h^{-1}

[a] LC_{50} = (Lethal Concentration Fifty). That concentration of a substance in air, exposure to which for a specified period of time, that is expected to cause the death of 50% of an entire defined experimental animal population.

TCLo = (Toxic Concentration Low). The lowest concentration of a substance in air to which humans or animals have been exposed for any given period of time that has produced any toxic effect in humans, or produced a carcinogenic, neoplastigenic, or teratogenic effect in animals or humans.

LCLo = (Lethal Concentration Low). The lowest concentration of a substance in air, other than LC_{50}, which has been reported to have caused death in humans or animals. The reported concentrations may be entered for periods of exposure which are less than 24 h (acute) or greater than 24 h (subacute and chronic).

ppm = parts per million
h = hour
mg·m^{-3} = milligrams per cubic metre
mo = month

Table 3. Threshold Limit Values (TLV) and Short-Term Exposure Limits (STEL) for some airborne pollutants.

Compound	TWA-TLV[a]		TWA-STEL	
	ppm	$mg \cdot m^{-3}$	ppm	$mg \cdot m^{-3}$
Hydrogen sulphide	10	14	15	21
Carbon disulphide	10	30	-	-
Methanethiol	0.5	1		
Ethanethiol	0.5	1		

[a] TWA-TLV = Time Weighted Average-Threshold Limit Value: the time-weighted average concentration for a normal 8-h working day, 40-h work week to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

TWA-STEL = Time Weighted Average-Short-Term Exposure Limit: the concentration to which workers can be exposed continuously for a short period of time without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency, and provided that the daily TWA-TLV is not exceeded. TWA-STEL is defined as a 15-min time-weighted average exposure which should not be exceeded at any time during a work day, even if the 8-h time-weighted average is within the TLV. Exposures should not be repeated more than four times per day. There should be at least 60 min between successive exposures to STEL.

ppm = parts per million

$mg \cdot m^{-3}$ = milligrams per cubic metre of air

Table 4. Effects of simultaneous inhalation exposure of laboratory rats to H_2S and CS_2.

Concentration[a] (A) CS_2 (B) H_2S	Exposure Period[a]	Observations	References
(A) 20 to 25 ppm (B) 20 to 25 ppm	4 $h \cdot d^{-1}$ for 150 consecutive days Rats	Increased reticulocyte count and globulin level, cholesterol rose 110th day, no abnormality in separate groups except for slight cholesterol elevation in H_2S group.	Kuwai 1960
(A) 0.032 ppm (B) 0.032 ppm	6 mo Rats	30% incr. blood cholinesterase, 14% incr. urinary coproporphyrin, 64% incr. plasma aspartate aminotransferase, and bronchitis. Only 16% incr. cholinesterase in (A).	Misiakiewicz, et al. 1972
(A) 10 $mg \cdot m^{-3}$ (B) 0.008 $mg \cdot m^{-3}$	24 h Rats	Poor muscle co-ordination, depressed cholinesterase activity, focal haemorrhage lung. CS_2 main agent.	Baikov 1963
(A) 300 ppm (B) 100 ppm	30 $min \cdot d^{-1}$, 4 mo Rabbits	Poor health and weight gain, decr. erythrocyte count, decr. haemoglobin.	Wakatsuki 1959

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[a] ppm = parts per million
$mg \cdot m^{-3}$ = milligrams per cubic metre of air
h = hour
d = day
mo = month
min = minutes

Table 5. Effects of exposure to combinations of airborne pollutants on animals.

Pollutant	Concentration[a]	Species	Observations	References
Hydrogen sulphide Ethylene, Propylene, Butylene, Butane	0.8 $mg{\cdot}L^{-1}$	Rabbits, mice, man	Conclusion that higher toxicity exists from a mixture of hydrocarbons with H_2S than from any of the components of the mixture.	Filippova 1963
Hydrogen sulphide, Ammonia, Carbon dioxide, Methane	<1 000 ppm <5 000 ppm <300 000 ppm <500 000 ppm	Poultry, swine, cattle	Manure from confinement units, breakdown of ventilation. (Review)	Taiganides and White 1969
Methylmercaptan, Dimethyl sulphide, Dimethyl disulphide, Equimolar mixture, Hydrogen sulphide	LC_{50}: 675 ppm 40 250 ppm 805 ppm 550 ppm 444 ppm	Rats	Reduced body weight. Total serum proteins increased, albumin and LDH decreased, liver damage.	Tansy et al. 1981
Hydrogen sulphide, Sulphur dioxide	0.0085 $mg{\cdot}m^{-3}$ 0.057 $mg{\cdot}m^{-3}$	Rats	Poor reflexes, decreased sulphydryl groups in blood and brain.	Sakhovs'ka 1967
Ethanol Hydrogen sulphide	0.33, 0.66 $g{\cdot}kg^{-1}$ 800 ppm	Rats	Became unconscious sooner than controls.	Beck et al. 1979
Hydrogen sulphide, Carbon disulphide, Dinyl	3.5 $mg{\cdot}m^{-3}$	Rats	Altered cholinesterase activity.	Mannanova 1964
Hydrogen sulphide Ozone Nitrogen dioxide Benzene-thiol Alpha-naphthylthiourea		Mice	H_2S gave greater protection against nitrogen dioxide than other sulphur compounds. Benzene-thiol protected against ozone. Alpha-naphthylthiourea and phenylthiourea gave some protection against nitrogen dioxide or ozone.	Fairchild et al. 1959.
Carbon monoxide, Hydrogen sulphide	0.3 $mg{\cdot}m^{-3}$ 0.05 $mL{\cdot}L^{-1}$	Rats	Marked toxic effect.	Melnichenko 1968
Hydrogen sulphide, Ammonia	20, 150 pmm 65, 150 ppm	Cattle	Eye irritation, altered respiratory rates, corneal damage, epistaxis, increased rectal temperatures.	Nordstrum 1975

[a] $mg{\cdot}mL^{-1}$ = milligrams per millilitre; ppm = parts per million; $mg{\cdot}m^{-3}$ = milligrams per cubic metre; $g{\cdot}kg^{-1}$ = grams per kilogram body weight; $mL{\cdot}L^{-1}$ = millilitres per litre.

Table 6. Reported observations of effects of exposure to gas well blowouts on animals.

Occurrence	Observations[a]	References
New Norway	Watery eyes and noses in cattle, diarrhoea in swine, pneumonia in swine and cattle.	New Norway Scientific Committee 1974
Lodgepole	Eye irritation, diarrhoea, decr. feed intake, excitement, nervousness, assisted parturition, weak calves, decr. milk yield, respiratory problems, coughing, reproductive disturbances, spontaneous abortions, unsatisfactory chemotherapy, weight loss.	Pembina Area Sour Gas Committee 1983
Lodgepole	Transient changes in activities of superoxide dismutase, glutathione peroxidase, glucose-6-phosphate-dehydrogenase, acetylcholinesterase, and aspartate aminotransferase.	Lodgepole Blowout Inquiry 1984
Lodgepole	Most producers feel there were no long-term effects on mature livestock. Problem animals were culled; herd performance back to pre-blowout levels. Now supplement with trace minerals (Cn, Zn, Se). Some concern for performance of calves exposed during blowout.	Harris 1986
General	Irritation of eyes and respiratory tract, respiratory problems, decreased production.	Beck 1986

[a] Observations made by veterinarians, farmers, and/or research scientists.

general, the homegrown crops tended to be low in selenium, sulphur, zinc, and copper. Soil samples were deficient in selenium and sulphur. The low sulphur content in the soil suggested that trace element deficiencies in the feeds of the area were not due to deposition of sulphur, but rather to naturally low levels of these elements in the soils (Prior et al. 1982).

A gas well being drilled by Amoco Canada Petroleum Limited in the Lodgepole-Drayton Valley area blew out of control on 1982 October 17, resulting in the emission of large quantities of natural gas, hydrocarbon condensates, and sulphur gases into the atmosphere over a 9-wk period. A study was undertaken by the Alberta Environmental Centre to determine whether or not exposure of cattle to the blowout emissions had an effect on the activity of five enzymes, namely superoxide dismutase, glutathione peroxidase, glucose-6-phosphate dehydrogenase, acetylcholinesterase, and aspartate aminotransferase. Blood samples were obtained from animals from each of 10 premises located at various distances and directions from the blowout site during the emission episode and on three occasions subsequent to its cessation, and from two control herds in the Vegreville area. These studies showed that some statistically significant perturbations did occur in animals within the exposure area. In all cases, the changes appeared to be transient and reversible (Lodgepole Blowout Inquiry 1984).

Twenty-eight beef cow-calf, swine, and dairy producers in the Lodgepole blowout area were interviewed to evaluate concerns about the problems which occurred during and after the blowout. The period 1980 to 1985 was studied. There were more problems identified during 1983 and the period following the blowout. In general, most livestock producers felt there were few long-term effects on the mature livestock within the area. The majority of the problem animals have been culled, and herd performance appears to be returning to the levels that were obtained prior to the blowout. On some farms, management practices have been changed to include trace mineral supplementation. Growth rates of young stock appear to be back to normal. There are some concerns about the performance of replacement heifers that were exposed as calves during the blowout. This report is subjective in nature since there is no concrete evidence to support many of the problems described or baseline studies to work from (Harris 1986).

6. CONCLUSIONS

There is little information on the actual or potential effects on livestock of sulphur compounds associated with the recovery and processing of sour gas, especially with respect to the identification and concentration of sulphur compounds.

If any effects occur in livestock, these are possibly the result of the simultaneous exposure to one or more sulphur compounds, together with a variety of non-sulphur compounds. The latter include ozone, ammonia, and the nitrogen oxides.

Under ambient environmental conditions, it is difficult to distinguish between effects induced by the exposure to airborne pollutants and those occurring as part of the spectrum of normal biological variation.

During periods of higher environmental concentrations, such as might occur during an industrial plant malfunction or sulphur block meltdown, a broader spectrum of pollutants may be present on a constant or fluctuating basis for varying periods of time. This transient and irregular characteristic makes it difficult to gather useful data.

Catastrophic events, such as sour gas well blowouts, may provide sufficient information to distinguish between induced effects and normal biological variation. Unfortunately, information on the concentrations to which affected livestock were exposed is rarely available in sufficient detail to determine a relationship between observed effects and the concentrations of airborne pollutants to which the livestock were exposed.

The effects induced by airborne pollutants must occur either in large enough numbers or with sufficient severity to allow their unequivocal identification and separation from the normal and expected biological values and events.

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HEALTH EFFECTS OF ACID DEPOSITION IN CANADA

by

B. Stern,[1] M. Raizenne,[1] R. Burnett,[1] and C. Franklin[1]

ABSTRACT

The health effects of acid deposition may be either direct (through contact with the air pollutant mixture) or indirect (through contact with media affected by the acidic pollutant such as food or drinking water). Although adverse direct health effects have been associated with high levels of acid air pollutants in both field and laboratory studies, it is not clear whether these specific pollutants are damaging to human health at commonly occurring environmental concentrations.

A study by Health and Welfare Canada investigated the chronic health effects of long-term exposure to acid deposition by comparing health responses between two populations of school children -- one residing in Tillsonburg, Ontario (high acid deposition area) and the other in Portage la Prairie, Manitoba (control area). After adjusting for confounding variables including parental smoking and socio-economic status, children in Tillsonburg exhibited a small (2%) but statistically significant decrement in lung function as compared with those in Portage la Prairie. Children in Tillsonburg also had a higher incidence of respiratory symptoms.

An acute summer study conducted by Health and Welfare Canada in central Ontario showed that levels of fine particles (PM2.5), average sulphates, and maximum daily ozone were significantly associated with a decrement in lung function in children attending a residential summer camp.

Further studies are underway to verify and expand these preliminary findings. Other studies investigating the health consequences of indirect exposure to acid deposition are also planned.

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[1] Environmental Health Directorate, Health and Welfare Canada, Ottawa, ON

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1. INTRODUCTION

The process of acid deposition encompasses both the wet and dry deposition of acid substances. Acid deposition may take the form of rain, snow, hail, or other wet precipitation. Alternately, it may be deposited as dust, impacted fine particulate aerosols, or by absorption of gas. Other pollutants, referred to as oxidants, are often associated with acid deposition because the same environmental conditions can lead to the formation and transport of both types of pollutants.

Sulphur and nitrogen oxides are the precursors of acid deposition. Once released into the atmosphere during, for example, the smelting of non-ferrous metals and the combustion of sulphur-containing fossil fuels, these primary pollutants may be transported by prevailing wind patterns over distances as short as a few kilometres or as long as several thousand kilometres. During transport, pollutants interact and undergo complex chemical transformations. The resulting pollutant mix, therefore, consists both of the oxides of sulphur and nitrogen and their transformation products, including sulphuric acid and nitric acid aerosols, ammonium sulphates, ozone, and small particulate matter, a large portion of which falls in the inhalable range (i.e., less than 10 microns in aerodynamic diameter).

The potential health effects of acid deposition may be either direct or indirect. Direct or pre-depositional effects of acid pollutants refer mainly to the inhalation of transported airborne pollutants, whereas the indirect or post-depositional effects involve the impact of acid deposition on drinking water sources and the biological food chain.

Although acid deposition has long been recognized as a serious environmental problem in Canada (NRCC 1981; Beamish 1974; Beamish and Harvey 1972; Schofield 1976), little is known about its effects on human health. Current ambient air standards exist for the pollutants NO_2 and SO_2, and for ozone; however, there are no standards in either the U.S. or Canada for many of the secondary transformation products such as acid aerosols, sulphate or nitrate-containing particles, and small particulate matter.

Investigations into the health effects of air pollutants fall under three categories of research methods: animal toxicological studies, controlled human exposure studies, and epidemiologic studies. Animal studies provide evidence about the mechanism(s) for action of pollutants. The results of these investigations, however, cannot be directly extrapolated to human exposures. Experimental studies on human volunteers can identify and often quantify human responses to individual pollutants; however, clinical exposures rarely last for more than a few hours and the health responses observed are usually acute and transient. The effects of long-term exposures to low concentrations of air pollutants cannot readily be studied by human chamber studies. Epidemiological studies can investigate the effects of both acute and chronic exposure to pollutants at concentrations commonly encountered in ambient air. This research approach, however, is complex and severely limited since it is difficult to associate observed adverse health effects to specific pollutants, or concentrations, and to exclude confounding variables that may contribute to the observed health effects.

On the other hand, convergence of results from multiple epidemiological studies with similar designs carried out by different investigators on different populations exposed to acid pollutants strengthens the interpretation of a single study.

As part of a national program to assess the risk to health posed by transported pollutants, two preliminary epidemiological studies were conducted in 1983 by the Canadian Department of National Health and Welfare (NHW). In one study, the health effects from acute exposure to transported pollutants were monitored by measuring changes in respiratory health indicators in asthmatic and non-asthmatic children during periods of high pollutant levels at a residential summer camp in central Ontario. The second study examined the effects of chronic exposure to transported pollutants by comparing several measures of respiratory health between two populations of school children: one residing in Portage la Prairie, Manitoba, where levels of these airborne pollutants are very low; the other living in Tillsonburg, southwestern Ontario, where levels of transported pollutants are among the highest in Canada.

2. SUMMER STUDY (1983)

Fifty-two children participated in the acute exposure study, which was conducted during a 10-day period in June to July 1983 at a summer camp on Lake Couchiching. The camp was located approximately 100 km north of Toronto, in a rural area remote from point sources of pollution but subjected to long-range transported acid deposition. The children ranged in age from 8 to 15 years; 23 had been medically diagnosed as asthmatic and 29 were non-asthmatics. Fifteen of the 23 asthmatic children in the study participated in a pre-camp clinical evaluation. A telephone survey detailing respiratory health history was completed for each participant in the study. During the camp session, measurements of lung function using standard methods were made twice daily on each child; respiratory symptomology questionnaires were also completed twice daily for each child, and activity patterns and levels during camp activities were profiled.

On site, continuous air pollution monitoring was performed and included measures of O_3, respirable and inhalable particles (PM2.5 and PM10, respectively), ammonium sulphate and bisulphate, NO_x, and SO_2. On-site meteorological measurements were conducted by Environment Canada.

Ozone levels at the campsite showed typical diurnal variations with elevated mid-day concentrations. The Ontario ambient air quality standard of 80 ppb for a 1 hr exposure to O_3 was attained or exceeded on 5 of the 10 days of the study, with the peak value (114 ppb) occurring on Day 4. Respirable fraction sulphates were highly variable, ranging from 10 to 26 $\mu g/m^3$. Sulphate as H_2SO_4 was very low, measurable at the detection level of the instrument (about 2 $\mu g/m^3$).

Preliminary analysis indicated that in both asthmatic and non-asthmatic children a small but statistically significant decrement in lung function--forced vital capacity, FVC, forced expiratory volume in one second, $FEV_{1.0}$, and peak expiratory flow, PEF--was associated with periods during which sulphates, ozones, and respirable particles were elevated.

3. CHRONIC STUDY (1983)

The respiratory health status of over 1400 schoolchildren aged 7 to 12 years was examined in Portage la Prairie, Manitoba and Tillsonburg, Ontario during the fall of 1983 and winter of 1984. Three measures of respiratory status were obtained for each child: (1) a questionnaire assessing chronic respiratory symptoms was sent home from school, completed by a parent, and returned; (2) bi-weekly telephone interviews with a parent (usually the mother) assessing the child's acute respiratory health status were conducted over a period of 18 continuous weeks; and (3) standard pulmonary function tests were performed. Sulphur dioxide, NO_x, total respirable particles, respirable sulphates, and respirable nitrates were monitored in both communities from October 1983 to March 1984.

Results were analysed using a multiple regression model and controlling for the effects of confounding variables such as socio-economic status, parental smoking, and the presence of a gas or wood-burning furnace in the home (Burnett and Kearney 1985). A small but statistically significant difference in two measures of pulmonary function was observed, with children in Tillsonburg showing a 2% decrement in FVC and a 1.9% decrease in FEV_1 as compared with children in Portage la Prairie. These comparisons have been adjusted for each child's age, height, weight, and sex.

With regard to respiratory symptoms, the presence of persistent chest cold was higher in Tillsonburg (38%) than Portage la Prairie (33%) at the 10% level of significance. More children in Tillsonburg exhibited "stuffy nose" and "cough with phlegm" than their counterparts in Portage la Prairie (25% versus 22% respectively for stuffy nose and 10% versus 8% respectively for cough with phlegm). There was a statistically significant difference in the incidence of inhalant allergies (allergies to smoke, dust, pollen, mold, or animal hair), with 13% of the children in Tillsonburg reporting these symptoms as compared with only 5% in Portage la Prairie. Fifteen percent (15%) of Tillsonburg children had been hospitalized before the age of two years due to a respiratory illness as compared with 12% in Portage la Prairie. There were no differences between the two communities in the incidence of children reporting asthma. Air pollution monitoring data showed that Tillsonburg had overall elevated levels of SO_2, respirable nitrates, and respirable sulphates, compared to Portage la Prairie. The ambient levels of NO_x and total respirable particles differed little between the towns.

4. DISCUSSION AND CONCLUSIONS

These preliminary studies conducted by NHW to assess the direct health effects due to long-range transported pollutants were designed to investigate the feasibility of conducting future large-scale epidemiological studies and to provide functional experimental models to evaluate both chronic and acute health responses to long-range transported pollutants. Data from both the acute and chronic studies suggest that there may be an association between acid deposition and respiratory health in school-aged children. Follow-up studies are therefore warranted and are currently in progress.

Two factors, however, complicate the interpretation of these data. First, although there is a town effect between Portage la Prairie and Tillsonburg, with children in Tillsonburg showing slightly lower levels of lung function and higher incidences of some respiratory symptoms, it is still not clear whether these differences are due to airborne acid pollutants or to some other, unknown characteristics that differ between the two communities and were not measured in this study, such as climate, lifestyle, or differences in indoor air quality. Second, the medical significance of small but statistically significant decrements in lung function and of differences in the incidence of respiratory symptomatology is not well understood. There is some evidence to indicate that a history of repeated acute lower respiratory infections in childhood may be associated with the development of chronic bronchitis or other chronic obstructive lung disease in later life (Reid 1969). It has also been postulated that a decrement in lung function parameters in childhood may similarly predispose individuals to develop chronic lung problems, especially if they are exposed to other airborne pollutants in adulthood, such as may occur occupationally or from smoking (Smyth et al. 1981; Groupe Cooperatif PAARC 1985).

Although the changes in respiratory health observed in both the acute and chronic studies are small, it is important that the relationship between the observed changes and acid air pollution be more fully understood. Other studies investigating the impact of acid rain on rural drinking water sources in areas affected by acid deposition are also being planned.

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PART 2: PANEL STATEMENTS

CURRENT STATUS AND FUTURE DIRECTION OF ENVIRONMENTAL REGULATION AND POLICY

Notes for Presentation to

A PANEL ON CURRENT STATUS AND FUTURE DIRECTION OF ENVIRONMENTAL REGULATION AND POLICY

Wednesday, May 14, 1986

Alistair D. Crerar

Chief Executive Officer, Environment Council of Alberta

The title of this panel is "Current Status and Future Direction of Environmental Regulation and Policy." I interpret that as suggesting we look at where we are (current status) and where we want to go (future direction).

That reminds me of a saying of an old Yankee philosopher named Yogi Bera, who said, "If you don't know where you're going, you'll probably end up someplace else."

Where are we trying to get to with environmental regulation and policy? What is the objective of environmental regulation? Where does policy want to take us?

Is the objective 20 kilograms per hectare, per year of wet sulphate? Is there some ecological effect we wish to achieve or prevent? For example, do we wish to prevent the reduction of pH by 0.1, 0.2, 0.3 anywhere beyond the plant gate of the emitter? Or is there some health criteria? Do we want to protect some segment of society? Do we conceive, for example, of asthmatics and allergics as society's "miner's canaries"? Is a world made safe for asthmatics a world safe for everyone? And do we wish to protect all asthmatics or only some percentage of them?

Questions of goals and objectives are not something that the Minister and his immediate advisors can sit down and decide. Of course, the Minister and Cabinet have to make the final decision on regulations and policy. But they need to have the views, not just of scientists and civil servants and the politically active but of all kinds of groups: health workers, educators, agriculturalists, municipal officials, and ordinary Albertans.

There is a session tomorrow on future needs and directions of research on acid emissions. I would submit that a high priority research issue should be the identification of the goals and objectives of the regulation of acid-forming emissions. We need to answer the questions, Why are we doing this? Where do we want to go? How can we tell when we have gotten there?

There are certain characteristics of air pollution that have to be considered in attempting to specify goals and objectives:

1. There is really no assimilative capacity for air emissions, there is only dilution.
2. There are distant impacts.
3. As we begin to realize more about volatilization, we can see that cross-media transfer is characteristic of air pollution.

These unique characteristics of air pollution suggest that we need to consider national goals and objectives. That doesn't make our task any easier. We already have some fairly clearly defined national goals and objectives. They don't apply particularly adequately to problems in Western Canada. In Alberta, for example, we have already achieved the major goal for Eastern Canada of 20 kilograms per hectare wet deposition.

Should we then be adopting the American approach, where the major goals and objectives are established on the basis of health criteria? Is our goal air that will be acceptable to healthy adults, or should it be acceptable to all, including asthmatics, infants, and the elderly? In the U.S., the goal for ozone is to "leave no more than 1% of the susceptible group vulnerable" (asthmatics, chronic bronchitis, etc.). Since the susceptible group represents 5% of the general population, about 120,000 people in the U.S. would be vulnerable. In Alberta, that would amount to 1,200 people. Since Alberta's standard is tighter than that of the U.S., it means about 800 people are vulnerable. If our standards were as low as Saskatchewan, it would be about 500 people.

It seems to me that to establish goals and criteria, particularly using such measures as the quality of health or the quality of the environment that you wish to achieve, we are talking about societal decisions and societal decisions have to be publicly arrived at.

There are many different ways of consulting with the public. You already do so by having someone like Dr. Martha Kostuch on your Steering Committee. You could do more by having the Steering Committee hold public hearings throughout the province and urge submissions from groups that would have substantial insights to contribute.

I would like to go over some of these potential presentors with you, because I think just by naming them one can begin to see the kind of contribution they might make. For example, you could have submissions from the Canadian public health associations, local public health units, associations of public health inspectors, the Canadian Cancer Society, and medical associations.

You could have submissions from the secondary educational institutes - from agricultural colleges and liberal arts colleges to universities and technical schools. They can provide valuable technical insights as well as identifying the role of education in, for example, environmental regulation.

If agricultural concerns are going to be part of your objectives or goals, then you should urge agricultural organizations to provide their views, such as Unifarm, Western Stock Growers, and Christian Farmers. Those who are concerned with some aspect of animal husbandry should be especially urged to contribute.

Because they are at the front line of contact with people, community organizations such as those for the MDs and counties and IDs and the cities, particularly those municipal organizations that have sources of acid-forming emissions located within their boundaries, should be heard from.

You should also consult with the generators of acid-forming emissions such as the oil and gas industry, the transportation industry and other major generators, and the unions that work in these industries.

You shouldn't miss hearing from the environmental organizations -- from FAN to AWA and various other groups - since they have major concerns and probably have valuable insights to contribute.

This is only a sampling of the kinds of contribution one could expect, and you should not overlook the contribution of ordinary Albertans expressing their concerns, their opinions, and their viewpoints.

I have been arguing that it is essential to have clearly identified goals and objectives. You could do so by having scientific advisors, civil servants, and the Minister sit down and decide for all of us what the appropriate goals and objectives should be. I would not advise that. I think the public of Alberta is too bright, too well informed, too concerned, too involved, to allow those major decisions to be taken out of their hands.

When dealing with air quality, the goals and objectives could be identified in a number of forms, such as:

1. health concerns (which is the major concern in U.S. legislation and which I have commented on)

but they could also consider:

2. agricultural productivity,
3. materials damage (to buildings, cultural artifacts, etc),
4. clarity (this is probably more prized in the West than in the East. In Toronto, I think they believe that a yellow haze is characteristic of fine weather.),
5. water quality effects (volatilization and air-borne transport is responsible for a substantial percentage of Great Lakes pollution), and
6. ecological disturbance (such as fish dieoffs or lichen disturbance),

or it could include a combination of some, or all, of these potential objectives.

Now, for those of you that suspect I am making these suggestions because I have a vested interest in public hearings, you are absolutely right. But my interest is not in proprietorship of public hearings but in the utility and effectiveness of the process. I don't know of a better way of collecting input from a diverse set of interests and creating an effective consensus than by a public hearing. However, there are probably other alternatives, such as:

1. Don't identify any goals and objectives.
2. Establish them by fiat. Or through consultation between civil servants and industry with the result endorsed by the Minister. That has been done in the past and could be done now.

3. Set up an Advisory Committee. The trick here is to select its composition and number.
4. Have workshops or open houses where the problem is discussed with interested members of the public.
5. Have public hearings with no provision made for keeping a record of what people said.

These are varying ways of letting people vent their concerns while maintaining control of the process. The last alternative is particularly subtle. If you leave enough time between the presentation to the hearing and the preparation of the report, fallible human memory guarantees that you can say there was "a general consensus in favour of ____________________, at the hearing in ________________________" and no one is in a position to refute you.

The choice of goals can only be effectively done openly and publicly. In my view, the best way of achieving that is through the public hearing process, one that encourages full participation and that respects the opinions brought before it.

However, a public hearing is useless, worse than useless, if:

1. It is conducted to legitimize a preconceived idea.
2. Is intended just to delay decisions or let off steam.
3. Has a panel hand-picked to give the results desired.
4. Doesn't really pay attention to what it is told by not keeping accurate, recallable records of what it has heard.
5. Does not search out and encourage new solutions to old problems. That's the greatest strength of public hearings. New ideas, new insights, new directions. They're out there.

Notes for Presentation to

A PANEL ON CURRENT STATUS AND FUTURE DIRECTION OF ENVIRONMENTAL REGULATION AND POLICY

Wednesday, May 14, 1986

Ian R. Smyth
Executive Director, Canadian Petroleum Association

1. The public's perception of what constitutes environmental protection has changed dramatically in 5 years. It has expanded from concerns for conservation and the protection of endangered species to embrace issues of public health and personal safety.
2. The public's level of interest in these issues has also changed dramatically. The issue of environmental protection has moved from interest through concern to the point where the need for environmental protection is firmly rooted in the value system of Canadians.
3. As a consequence of these trends, environmental protection has acquired political significance that continues to grow. Simultaneously, the public interest groups that articulate environmental issues of various kinds have become increasingly sophisticated, politically influential, more technically competent, and more responsible in their dealings with government and the private sector.
4. Given these factors, we must expect that there will be a continuing and, likely, a growing demand for better environmental management and that at least part of that demand for something "better" will be reflected in demands for more control in the form of standards, monitoring, and enforcement.
5. While demands for better environmental control are likely to grow, there is a parallel thrust for deregulation and, therefore, the corresponding need to ensure that the forms of control we employ are cost effective. In this context, it is well to remember that more regulation does not necessarily mean better control. Indeed, rigid systems of control that

regulate not only what is to be achieved but how it is to be done are likely to kill initiative, flexibility, sensitivity, and innovation if the focus is on adherence to rules rather than on results achieved. Procedural rectitude is the first refuge of a bad manager.

6. With few exceptions, people in our industry have long since learned and have honestly tried to act on the belief that good environmental management is good business. We have also learned that bad environmental management - or even honest mistakes which lead to accidents - can be very costly for an individual company and sometimes for the industry as a whole.
7. Recognizing that current trends are likely to increase the need for good environmental management, we are seeking in all jurisdictions, federal or provincial, a policy and regulatory regime that focusses on better, rather than more, control. We believe that a system based on accountability for results achieved, or not achieved, offers significant advantages over one based on tightly structured rules and regulations.
8. We also recognize that any initiative by the industry to be more self-regulating and, therefore, more accountable carries with it a companion imperative in terms of public information and, in particular, explicit recognition of the legitimacy of responsible public interest groups in the planning process. In that context, we also believe that if we are going to earn the trust of the public we must begin by recognizing that, in any given situation, it is highly unlikely that the stakeholders will buy into the solution if they weren't around when the problem was defined.
9. Much of this approach is already operative within the member companies of the CPA. Indeed, much of our environmental committee work in recent years has focussed on the development and dissemination of standards and guidelines for good environmental practice within our member companies and the industry as a whole. We have also committed large sums of research (the ADRP is a case in point, but there are dozens of others) in order to ensure that good science is available to assist in decision-making. This being said, it must also be recognized that we are an association, not a police force, and, while we speak for a very large slice of the industry,

we do not speak for the industry as a whole, nor do we have any power to enforce good performance. We believe that good performance is good business, and, therefore, we would like the policies and system of administration that govern us to reward the good performers and to discipline the bad ones. What we do not need is a system based on the premise that we're all bad from the outset.

10. What we do want, as I indicated earlier, is a system in which accountability has a significant role and that, in turn, implies the existence of agreed standards of performance that flow from proven technology and good science rather than emotive rhetoric and subjective measures. We are all tired of non-quantitative statistics, I think. So long as standards, measurement, and enforcement are operative and visible, the opportunity exists for us in industry to develop cost-effective approaches to good environmental management rather than having them designed for us by others. Despite our financial circumstances, good environmental management remains a high priority with us. As the need for more and better performance increases - and it almost certainly will - we will all have to find ways to meet the need without destroying project economics.

Notes for Presentation to

A PANEL ON CURRENT STATUS AND FUTURE DIRECTION OF ENVIRONMENTAL REGULATION AND POLICY

Wednesday, May 14, 1986

M.J. Chorel
TransAlta Utilities Corporation

Acid-forming emissions continue to be a major environmental topic. Only in the field of lake and other water studies have cause and effect relationships been determined, so there is a great deal of information yet to be gathered.

While it appears the government may be moving to more strict, encompassing environmental regulations, TransAlta agrees that the research taking place in our province needs to be completed before further environmental guidelines are developed. Given the existing stringency of Alberta's environmental regulations, we need to know what the cause and effect relationships are between emissions and environmental response before making regulatory changes. Regulations with a good basis in knowledge are far more acceptable to all.

A good example of the need for further investigation is in the area of trace elements. Although a recent Canadian Electrical Association study shows that trace element loadings from thermal power plants are low and pose no problem to the environment, a study done by Syncrude indicates that trace elements are accumulating at low levels in the environment around the oil sands facilities. Additional work needs to be done to better understand trace elements.

When talking about environmental regulation and policy, it is important to remember that, from a utility point of view, western Canadian coal contains one-twentieth the sulphur content of eastern Canadian coals. This low-sulphur coal, coupled with stringent provincial regulations, already ensures minimal environmental impact. Another advantage we have in Alberta is the highly alkaline content of the soil. The soil acts as a buffer for acid emissions. An initial assessment of Alberta's acid deposition problem makes it seem less severe than that in eastern Canada.

It appears, as a result of these proceedings, that nitrogen oxides are receiving more attention. Regulation of nitrogen oxides appears likely because of their contribution to acid rain. Our experts are learning more about how nitrogen oxides react in the environment, forming acidifying compounds. In the future, more attention will be given to emission rates of nitrogen oxides. Policy-makers at the Muskoka '85 Acid Rain Conference referred to this need. Already, control of nitrogen oxides has been increased in Japan and the United States. We at TransAlta are pleased that the Alberta government is collecting more information on acid loadings before changing any existing guidelines or policies.

The development of reasonable environmental policies and guidelines is becoming more complex with time. As we learn more and more about interaction between pollutants, the process of developing guidelines will become even more complex.

Rapidly advancing technology has given us the ability to measure elements at smaller and smaller concentrations, but that ability is becoming greater than our knowledge of the effects of the elements being measured. This adds further complexity.

Another factor to be considered in environmental regulation is cost, which is borne by the consumers. Any increase in environmental standards a utility must meet translates directly into an increase in consumers' electric bills. Society must balance appropriate levels of environmental protection with the increased financial burden. Many surveys indicate that the public wants increased environmental quality with no increase in electric rates, and that is not possible.

Thus, utility policy must be tempered by cost and the effectiveness of environmental control. Recently-adopted Alberta emission guidelines will likely require sulphur removal on almost all future thermal generating units. This could add up to 20% to the capital cost of power plants. Current conventional equipment to remove sulphur, in the form of flue gas desulphurization units, or scrubbers, would increase the cost of environmental controls to almost one-third of the total cost of power plants. This would have the effect of increasing electric rates by up to 12%.

Electrical utilities contribute 10 to 14% of acid emissions in Alberta. TransAlta is conscious of, and concerned about, the impact of its operations on the environment. Active in the Acid Deposition Research Program with the Canadian Petroleum Association, the ERCB, and government, TransAlta has taken an interest in the development of new technologies as they apply to the electric utilities. The company continues to seek cost-effective solutions to new regulatory requirements and newly identified areas of concern.

TransAlta has become involved with other interested companies in various new trends in generation development and emission control. For example, TransAlta, along with several U.S. utilities and Rockwell International of California, has been developing a new combustion technology. This technology, which has been under investigation for about six years, is expected to substantially reduce sulphur emissions from coal at what is hoped will be a fraction of the cost of conventional flue gas technology.

Initial tests of the combustor on low-sulphur coal show successful removal of sulphur by approximately 70%, nitrogen oxides reduced by about one-quarter the emission from conventional plant, and removal of up to 80% of coal ash. This is, we feel, an encouraging reduction in emission levels.

The next phase of the research program involves the installation of a prototype burner at our Wabamun Generating Plant west of Edmonton. Engineering will begin in mid-1986, with program completion scheduled for mid-1989.

A second promising technology in which TransAlta is actively participating is the coal gasification combined cycle power plant, CGCC. In this process, coal is turned into gas, which then fuels combustion turbines. The CGCC process offers the advantages of reduced environmental impact and increased efficiency. Thermal conversion efficiency of this technology is about 5 to 10 percentage points higher than conventional coal-fired power plants, which are in the range of 33 to 35%. Environmental advantages include: removing sulphur from the synthetic gas stream, water requirements half that of conventional coal-fired plants, and lower land requirements. We expect the technology to provide greater scheduling flexibility. Smaller-sized modular generating units and shorter lead times should make it easier to match capacity additions for increased electrical demands.

TransAlta has engaged an equipment supplier to study the CGCC process for application in Alberta. Phase one of the research program, completed this spring, involved testing Alberta coal samples and estimating the cost of both a prototype and a commercial plant. The next phase involves testing 25 to 50 tonnes of Alberta coal at a United States test facility. Depending on the results of this study, further phases would involve the design and construction of a prototype plant and, later, a commercial facility. Commercialization of the technology, if successful, could take place by the mid-1990s.

These two activities in which TransAlta in participating address both environmental concerns and the cost to the electric consumer. We at TransAlta feel we are well on the way to controlling both sulphur dioxide and nitrogen oxide emissions from Alberta's low-sulphur coal. As investigation into the Rockwell combustor, the CGCC, and other technologies continues, we feel we can contribute to maintaining effective environmental controls without creating a burden for Alberta electric consumers.

These research projects, we believe, will achieve our objectives of meeting environmental concerns with a lower cost alternative. Potential technologies like the Rockwell combustor and CGCC make it easier to adapt corporate policy to changing environmental regulations.

Since Alberta already spends substantially more money per capita on pollution control expenditures than any other province in Canada, let us ensure that the money is well spent and that environmental regulations truly reflect environmental conditions in Alberta.

Notes for Presentation to

A PANEL ON CURRENT STATUS AND FUTURE DIRECTION OF ENVIRONMENTAL REGULATION AND POLICY

Wednesday, May 14, 1986

Vern Millard

Chairman, Energy Resources Conservation Board

1. INTRODUCTION

Research must play an integral role in the establishment of environmental regulations and policy. During the last two days, I have listened with great interest to the description of various research projects relating to the impact of acid-forming emissions. While listening, I have been speculating as to how people residing near either operating or proposed emission sources (such as sour gas plants) would react if they were in attendance. My hunch is that they would not be overly influenced.

I must clarify that latter statement before you draw the wrong conclusion. The ERCB in the course of its activities frequently ends up in meetings with people residing near proposed sour gas facilities, who express concerns about potential impact. The concerns usually relate to possible impact on their health, on their safety, and on their agricultural operations. Understandably, local people are worried about becoming ill from the plant emissions or about their farming or ranching operations being seriously impacted.

If they were present at this symposium, I suspect they would ask whether the substantial research conducted to date would provide answers to their concerns. In other words, will the level of emissions that are projected from the proposed plant have a deleterious impact on health, soil acidification, livestock, etc.

I am under the impression that the research programs that have been developed have not been directed to answering those particular questions. I recognize that they probably help answer them, but the connection is far from direct. Indeed, I think it would be fair to say that the researchers are generally unaware of the problems perceived by the local people and that, clearly, the local people are unaware of the research that has been and is being conducted. As a result, the problems that local people identify with sour gas and similar kinds of facilities continue unresolved. However, research continues unabated and, indeed, appears to be increasingly specialized and sophisticated. This gap between the public for whom the research is presumably being done and the researchers reminds me of two trains on two parallel tracks passing each other in the dark with no terminal at which to meet and discuss their mutual interests.

Does the system really need to operate in this fashion? I suggest it does not. To support that view I wish to draw on a recent case where the parties are getting together to discuss mutual problems.

2. THE FORT MCKAY EXAMPLE

In 1984, the ERCB considered an application by Syncrude to expand its oil sands mining and upgrading operation. The proposal envisaged increasing throughput at the plant but decreasing SO_2 emissions by the addition of hydrocracker and sulfreen tail gas cleanup facility. The Syncrude and Suncor plants are located about 10 miles south of the small native settlement of Fort McKay. Total emissions from the two plants are about 450 tonnes of SO_2 per day. The hearings were adversarial and divisive. The community presented a panel of witnesses who contended that the oil sands plants had destroyed their way of life, created intolerable pollution impact on their community, and was threatening the health of the residents. Syncrude presented summaries of the substantial research and monitoring programs that had been carried out in the area by both industry and government, to demonstrate that the environmental impact was limited and well within acceptable standards.

The Board granted the application because it was in everyone's interest, including the community, since it would result in lower SO_2 emissions. It also concluded that the tremendous gap in belief about the impact from the two plants should be resolved. If the community's views were correct, then, clearly, remedial measures should be taken. If they were not correct, then the community deserved to have their fears allayed. Therefore, we set out to find a means whereby that resolution could be accomplished. Perhaps what is important to this symposium, however, is that the extensive research undertaken in the oil sands area obviously had no effect on the concerns and problems of the local community. That situation is not surprising, because the community had no knowledge of it and no input into it.

I won't bore you with all of the developments that have occurred since 1984, but I can report that the situation is beginning to change. The major change is that the community, the operators, and government departments are now talking with each other. The research that has been conducted is being reviewed for the community by Dr. Ron Wallace. The community has established an Environmental Educational Committee and is on the verge of playing an active role in the monitoring, surveillance, and reclamation programs. The research that has been completed is being tested to see whether it answers the specific concerns of the local people. I expect that gaps will be identified and that new research projects will be undertaken to close those gaps.

In summary, environmental research in the oil sands mining area is being turned around to ensure that it serves the needs of all parties, including the local people.

3. CAN THE FORT MCKAY EXPERIENCE BE EXPANDED TO OTHER AREAS?

On many occasions, a proposal to build a sour gas facility leads to widespread concerns in the local community. The Board is currently faced with four active cases at this time. The concerns are not new; we have heard them on many other occasions. In other words, we know the issues that will cause problems for people living near those plants. We also know the air quality and other standards. We know a good deal about the actual operations of existing plants. Indeed, we have mountains of monitoring data on certain aspects of those operations. Those data provide us with the actual results from plant operations and permit comparison to the standards and actual conditions in other jurisdictions. Unfortunately, we rarely take advantage of those data, and we don't appear to relate our research findings to those actual or predictable conditions.

A study made by the ERCB a couple of years ago respecting SO_2 concentrations recorded by monitoring units near sour gas plants revealed that, on average, actual concentrations were less than 0.02 ppm for 97.5% of the recorded hours. For another 2.3% of the recorded hours, the concentrations were between 0.02 and 0.06 ppm. In other words, for 99.8% of the recorded hours, the SO_2 concentrations at specific monitoring stations near the plant were less than one-third of the Alberta standard and one-sixth of the acceptable standard established by Environment Canada. The monitoring locations were selected by Alberta Environment to represent areas most susceptible to high concentrations.

The air-quality standards are designed to protect the health of people and the environment, including the capability of agricultural land. The Canadian standards, particularly the desirable standard adopted by Alberta, is one of the most stringent in the world. It is almost one-half the standard recommended by the World Health Organization.

I suggest that we need to find ways to copy the Fort McKay experience. Instead of simply carrying out more and more sophisticated research, we need to decide whether we can answer the current problems that local people have identified. The local people are concerned about health and agricultural impact. Alberta air-quality standards are designed to protect both health and the environment. Actual concentrations in the area nearest the plants are only a fraction of those standards. I submit that it is time we developed a consensus by the researchers as to whether those conditions constitute a risk to people nearby.

Expressed another way, we need to draw on the research that has already been completed and relate it to actual operating conditions and decide whether it is reasonable to assume that there might be either health or environmental problems under those conditions.

PART 3: SUMMARY REPORT ON THE WORKSHOP SESSIONS

ACKNOWLEDGEMENTS

The success of this workshop rests primarily with the 60 to 70 attendees who provided their valuable and thoughtful input to the group discussions.

The workshop and follow-up report was made possible with the commitment of the following CPANS/APCA members and their employers to this important subject to acid emissions and their effects in Alberta:

David Chadder, Promet Environmental Group
Howard Heffler, Tera Environmental Consultants
Lynda Holizki, Alberta Energy Resources Conservation Board
Don Johnston, Dome Petroleum and University of Calgary
Douglas Leahey, Western Research
Dennis Leask, Mount Royal College
Chow-Seng Liu, Alberta Environment
Nicola Ross, Concord Scientific
Bill Schnitzler, Alberta Energy Resources Conservation Board
Al Schulz, Alberta Environment
Steff Stephansson, NOVA, An Alberta Corporation
Phillip Ullman, Environmental Management Associates

In addition, the efforts of Mr. Brian Croft, Dome Petroleum, as Workshop Chairman, and the assistance and support of Mr. Don Colley, Western Research, and Mr. Ed Brushett, Alberta Energy Resources Conservation Board, in organizing the Workshop are most gratefully acknowledged.

INTRODUCTION

This workshop was the second of this type held in Alberta. The first was in Edmonton, on 1982 March 9-12, at which the attendees were free to attend one of four sessions: Air, Aquatic, Terrestrial, or Health.

The objective of that workshop was to identify important scientific research needs.

The 1986 workshop had its objectives expanded somewhat from 1982, in directions beyond science and technology to related matters such as public concerns, political and financial issues, and the role of communication. The specific objectives were as follows:

1. To provide an opportunity for people from all sectors (industry, government, university, environmental consultants, and the public) to express their ideas and concerns on the issue of acid deposition;
2. To identify and provide the rationale for future research needs; and
3. To provide an objective written summary of the workshop conclusions.

The workshop was preceded by a two-day symposium at which researchers and experts addressed the various areas of concern related to acid-forming emissions and their environmental effects.

CPANS/APCA ROLE

In order to meet these objectives, it was decided by the Steering Committee to invite the Canadian Prairie and Northern Section of the Air Pollution Control Association (CPANS/APCA) to organize and carry out the workshop. This was agreed to, and a team of facilitators was put into place under the Chairmanship of Brian R. Croft, a past-chairman of CPANS/APCA.

The goal of CPANS/APCA was to ensure that all attendees were given adequate opportunity for discussion and that meaningful issues and recommendations would be identified by participants. Furthermore, it was also an important goal that a fair and objective summary report of the discussions would be provided to the Steering Committee.

To prepare the facilitators, a special "Workshop Leadership Training Course" was arranged by CPANS/APCA. The course was presented by Murray Hiebert and Colleagues of Calgary. While at this course and as part of it, the facilitators developed the workshop agenda. This was a most difficult task in itself because of the concerns for short workshop time availability, the expected large number of attendees, and the need to allow discussion yet achieve consensus on priority issues.

Following the training course and two weeks prior to the workshop, all facilitators were provided with a detailed breakdown of activities and responsibilities for the workshop sessions. This was followed up on the day before the workshop with a review and clarification meeting.

WORKSHOP AGENDA

The basic workshop agenda was as follows:

8:00 to 10:00 - Issue Identification
- Attendees were randomly divided into six groups of equal sizes
- Six workshop groups met separately
- Goal--consensus on highest priority issues

10:00 to 10:30 - Coffee

10:30 to 12:00 - Presentation of Issues to All Attendees
- A general session was held
- Facilitators presented issues beginning with high priority items
- Clarifying discussion, questions, and answers on issues

12:00 to 1:15 - Luncheon Meeting of Facilitators and Steering Committee
- Issues were grouped into common areas

1:15 to 3:00 - Research Recommendations

- Attendees were free to go to the group of most interest to them
- Each group discussed a particular subject area
- Goal--consensus on most important research needs

3:00 - Workshop ends, attendees return for symposium closing

Following the workshop, all facilitators prepared summary reports of the discussions and conclusions from their sessions. In addition, the facilitators made suggestions on areas of possible improvement for any future workshops.

IDENTIFICATION OF ISSUES

Six groups met concurrently to address the question "What are the issues in terms of the future needs and directions of research on acid emissions in Alberta and their ecological effects?" Each group was responsible for identifying six high priority issues. Priorities were based on the discussions and general consensus of the group. Some groups identified many more than six issues, in which case they attempted to assign priorities.

The top six issues of each group were reviewed at a general session, and it became apparent that there were many that were similar. This was encouraging, since it showed that there were issues of a high priority to more than one group.

The issues from the six sessions were grouped together into four common areas as shown below. The issues are presented as identified by each of the six sessions so that any unique factors are not lost.

1. COMMUNICATIONS

- Definitely a need for long-term research, but is there a commitment by policy-makers for long-term research?*
- How well focussed and co-ordinated are research efforts at present?*
- Ensure government, industry, and public have input into loading standards.*
- Ensure that there is a broader information and technology exchange.*
- Regulatory Procedure - Regulations relating to emissions and monitoring of acid-forming substances should be derived from an approach that uses results of scientific research. Input should be solicited from all interested parties.*
- Need to effectively and credibly communicate acid deposition issues to the affected and/or concerned public. Rationale - Need to let the public know the full extent of research results so they may understand what has/is being done and reach reasonable conclusions; credibility is very important.*
- Decision-making - A massive amount of data is being gathered. It tends to overwhelm the decision-makers, so a mechanism to use this information for political and regulatory decisions must be developed.*
- Credibility - There is a tendency for the public to be skeptical of information coming from both government and industry. Information releases must be credible and should describe not only the results but their interpretation and should include a statement of what will be done next. To date, there is no evidence of significant ecological effect by acid deposition in Alberta.*
- Technical Assistance - Often the public is called on to respond to highly technical information. There should be a vehicle to allow the lay public to obtain technical assistance.*

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* These issues were considered as one of the top priorities by a group.

- Need to characterize and quantify socio-economic risks associated with acid deposition (perceived and real). Cost-benefit to be considered.*
- Improve methods for consensus building -- provide for public awareness/acceptable or rejection.*
- Information Sharing - Need more open information.*
- Need to communicate to public a realistic and credible presentation of issues more related to Western Canada.
- Need to involve public more in co-ordinated effort of data presentation and interpretation.
- How can public figure out who is co-ordinating the research?
- Issue Definition - Is there a problem?
- Should improve Canada-U.S. relations with respect to acid deposition research.
- Communication - Transmittal of research results should be improved with the aim of educating the public about the many facets of acid deposition, including seasonal variations, geographical distributions, and political-economic considerations.
- The issue of co-ordinating the many groups who are undertaking research into this area was a real concern. However, we were assured that ADRP was addressing this issue. If this were not the case, it would be a priority issue.
- Communication - The results of ADRP and other programs must be broadly communicated to the public. Technical exchange within the scientific community is also important.
- Technical Information - Exchange of technical information among the scientific community (including international) is important.
- Regulatory Process - More dialogue is needed internationally; especially with the U.S.
- Study or research on communication mechanism for presentation and discussion of concerns from all parties.
- An independent, unabiased person/office is needed to work with local people on hearings by arranging meetings, by organization, and by education -- an environmental advocate.

- Public input is needed into government mechanisms, policy, and research.
- Need a mechanism for ownership and accountability of decisions on environmental issues by government, industry, and the public, need for honesty.
- Acceptance of research should be done by peer review -- on an international scope (journals).
  - Make sure information is given wide scientific exposure.
  - Peer review before and after studies are carried out.
- Public Education - How to educate the public and industry to avoid antagonism and to foster understanding, communication, and media involvement.
- Co-ordination of effects research on transboundary pollution.
- More communication and co-operation on research.
- Need to obtain public acceptance of industrial development and operations.
- Support of intervenors input (technical and financial, etc.) to industrial development, need to fully understand impact of new projects.
- How to deal with transboundary pollution transport? Measurement issues.

2. MONITORING AND MODELLING

- Need better monitoring on biological and ambient environment.*
- Identify and characterize pollutants in terms of wet/dry components.*
- We should establish acceptable deposition rate standards; at present, we have one for the east but not one for the west.*
- Loadings to the environment*
  - Ensure that current loadings are proper and correct to prevent damage.
  - Ensure that monitoring systems provide useful and reliable data.
  - Develop enhanced dry deposition monitoring systems.
- All forms of model studies must be verified to be applicable in areas where they are used.*

- Further research to ensure an understanding of acid deposition in terms of other pollutants such as organics and heavy metals.*
- Understanding - Research should be undertaken with specific goals such as determining the relative roles of wet and dry deposition, the need for a calibrated watershed-type study, the chemical composition of rivers, the base losses in soils, and the amount of magnesium sulphate in lakes.*
- Perspective - Measurements and monitoring requirements should be brought into balance with interpretation abilities. This would mean, for example, that efforts should not be expended to develop instruments for purposes of assessing ambient concentrations of sulphur dioxide in parts per trillion when we cannot evaluate the effects of such small variations on the functioning of the ecosystem.*
- Data Deposition - All data relating to research projects should be collected and formatted in a conveniently usable manner and made available for use by the scientific community.*
- To obtain baseline data about natural systems: deposition, air quality, and the ecosystems including processes. Rationale: Above all else, high quality data is fundamental to successful understanding of the effects of acid deposition; need for a good network of quality monitoring stations.*
- To prepare an inventory of alkaline and acidic deposition by monitoring wet and dry deposition. Rationale: This is the next step beyond emissions data collection; need to be more specific in what we measure; contribution of alkaline (dust) distribution in Western Canada is largely unknown.*
- To quantify the sensitivity of water and soils in Alberta (Western Canada). Rationale: How and to what degree are these systems able to respond (cope) with acid deposition? This is not an inventory but, rather, a development of a quantitative measure; includes assimilative capacity, not just initial process/response to acid deposition loading.*
- To design a good measurement technique for dry deposition. Rationale: There is no good method.*

- A need for additional wet and dry deposition monitoring.
- A need for development of biomonitoring techniques, especially with respect to understanding long-term effects.
- Develop biomonitoring systems as a means of inexpensive measurement media.
- No adequate biomonitoring programs currently in place to warn of developing problems.
- Modelling - We cannot monitor everything and the future can only be modelled. Modelling is needed.
- Establish data base.
  - National data base is needed.
  - A lot of data has been collected - how much is being used?
  - Slow data release to public and researchers.
  - Data in too many forms.
  - Collect in usable form.
  - Rationalize data base.
  - Adjust data base to answer questions.
- Research into distinguishing between local and distant sources.
- Sensitivity mapping to identify sensitive areas of the province.
- A procedure for reviewing and updating regulations regarding current monitoring parameters.
- Dry Deposition - It is very important to find a way to assess the contribution of dry deposition to total pollutant loading. This includes measurement of the effect on pH and SO_4 by wind-blown dust.
- Modelling - There is a need for better short-term meteorological forecasting to allow predictive models to be tied to emission controls.
- There is a need for better models to describe integrated effects to the ecosystem.
- Monitoring - The transboundary input into Canada should be measured.
- A routine air-quality monitoring network should bet set up in Alberta.
- Data Base - A central repository of data should be developed to collect, analyze, and disseminate information.

- Atmospheric Modelling - Need qualitative and quantitative characterizations of regional scale transport and deposition (wet and dry).
    - Dust - understand role and modelling
    - Evaluate models for local applicability
- Acid Deposition - Long-term effects on soils and surface waters and their interactions needs to be measured and understood.
- What is the acceptable target loading? What is coming down?
- Sensitivity of Organic Soil Systems - Test the criteria used for sensitivity rating.
- Surface Water Acidification - Mechanisms: natural, man-made.

3. BIOLOGICAL EFFECTS

- Establish effects on the ecosystem by developing predictive capabilities of ecosystem effects.*
- Further research on how acid-forming compounds and management practices will have an impact on the dose:response relationships in areas such as farming, aquatics, forestry, and health.*
- Integration - Results of specific research projects should be integrated with information derived from health studies to obtain a comprehensive overview of ecological effects of acid-forming emissions.*
- To study the effects of acid-forming emissions on human and animal health in close proximity to the source(s). Rationale: Need for cause and effect studies; medical diagnostic review is epidemiological; nothing being done for animal health.*
- Biological - What is the acceptable target loading in terms of biological effects (human, soils, aquatic, vegetation).*
- Is human health an issue or not?
- Impact on natural vegetation, especially forest by air pollutants, e.g., ozone. What are the natural and anthropogenic causes of stress?
- Ecological effects of sulphur-related compounds specific to Alberta, including health effects.

- Threshold limits of our terrestrial systems to acidification.
- Mechanism to investigate health issues and public concerns.
- Characterize and quantify risks associated with acid deposition.

4. EMISSION CONTROL TECHNOLOGY

- Prevention/control strategies/cost-benefit; should concentrate on prevention.*
- Increased focus on abatement and reducing emissions.*
- Control Technology - Most research seems to be directed to "effects" of acid emissions. There is also a need for research and development on new and improved emission control methods. Perhaps radically new ideas can lead to improved treatment.*
- Technical development for better emission control (to make best available technology more cost effective).*

RECOMMENDATIONS FOR FUTURE RESEARCH

The issues identified in the morning group sessions were divided into four areas of common concern. These were discussed in the afternoon and the following recommendations were identified:

1. COMMUNICATIONS

Facilitators: Nicola Ross, Bill Schnitzler, Howard Heffler

Introduction

The Communications group included 15 participants who attempted to develop specific recommendations dealing with the issues from the morning sessions. Notes from the summary sessions from 10:00 a.m. to 12:00 noon were used to guide the discussion.

Discussion

There was lively discussion from all participants. The starting point for each topic was taken from the issues identified in the morning. The focus of the discussion was to find recommendations to ensure the results of scientific/technical studies were communicated to the public.

Seven recommendations were developed. These recommendations and the supporting rationale were:

a. The group generally supported the activities of the communication program of the Acid Deposition Research Program (ADRP). However, a validation program measuring the success of the communication program should be developed.
Rationale: The participants who were intimately familiar with the ADRP gave many examples of how the communications program was responding to the requests for information and how the public was involved in the program. However, those who were less familiar with ADRP were not aware of this. The group felt the ADRP communications group sounded good, but they wanted to see something to confirm the effectiveness of the program.

b. **Annual reports, fact sheets, or information packages should be developed on request and presented to the public. This task should include input from many sources (i.e., AE, ERCB, CPA, public). A co-ordinating committee needs to be put in place to ensure the information is being prepared and is consistent.**
Rationale: Many times the same type of information is requested by different parties. To expedite the response, a standard package on popular themes could be developed. Since many groups may have information which is relevant to the information package, they will all want to have input and their input must be co-ordinated in some way. The group recognized the complexities of this approach but felt it warranted the effort.

c. **Alberta Environment must be encouraged to get its reports out in a timely fashion.**
Rationale: Several members of this group commented that obtaining information from Alberta Environment is slow.

d. **The scientific community should ask ADRP for information, and it will be provided if at all possible.**
Rationale: The information being developed by ADRP is of wide interest to the scientific community as well as to the public. The ADRP is prepared to provide responses to requests from other scientists and will do so as well as possible. In part, this is to avoid the potential of unnecessary duplication of effort.

e. **There is a need for an annual forum to present results of the ADRP for discussion with technical community and general public.**
Rationale: In addition to ADRP responding to specific information requests, the program should make a regular effort each year (such as via a workshop like the present one) to keep the interested public up to date.

f. **Alberta Environment should supply assistance to public groups so they can participate equally in a hearing process. There are already good processes in place by the ERCB for specific projects**

and some specific issues. This practice would require the development of stringent qualifications and criteria for receipt of assistance.

Rationale: The ERCB has a good set of procedures in place to allow funding of bona fide intervenors at board hearings. No such mechanism exists for Alberta Environment. Without it, there was general agreement that the public can be overwhelmed by high-priced, technical experts, and they cannot compete fairly.

9. **The ECA should hold hearings into acid deposition.**

Rationale: Some members of the group felt the whole issue of acid deposition in Alberta merited wide public debate. One vehicle for such a process would be a public hearing by the Environment Council of Alberta. Other members of the group did not feel there was enough concern in the province to warrant a hearing but felt that the existing technical work now underway was sufficient. The resulting recommendation was put forward without unanimous agreement.

2. MONITORING AND MODELLING

Facilitators: David Chadder, Lynda Holizki, Chow-Seng Liu, Al Schulz

Introduction

Those in attendance were asked to identify the future research requirements for monitoring and modelling. It was understood that both play an integral role in acid-forming emissions research. From this session came five main areas for future research in Alberta, all of which should be investigated equally for assessing the complete impact of acid-forming emissions. No priority was given to the order of their importance. The five research areas include: monitoring, modelling, dry deposition, wet deposition, and data integration.

a. Monitoring

- **Standard monitoring methods should be developed for soil, water, and air on as broad a basis as possible. Standardized programs should be considered on at least a national, if not continental, scenario.**

- It is important to identify and characterize additional pollutants, at least by qualitative analysis methods.
- Biomonitoring methods should be investigated.
- Benchmark monitoring for acid emissions and their effects should be implemented, especially where sensitive areas and high-plume-level impingement zones are concerned.
- There is uncertainty as to the role of dust. Hence, it is recommended that a review of emissions of windblown dust be undertaken. Specifically, monitoring for particulates and their constituents should be implemented.

b. Modelling

- Because models are important to our understanding and prediction of the acid deposition problems as well as the assessment of biophysical impact, it is necessary to continue to develop and validate models for the biophysical system.
- The validation of models should be carried out with "real data" or proper observation datasets (using standardized methodologies). The validation step is important, because it evaluates model performance, establishes its accuracy, and assesses its usefulness.

c. Dry Deposition

- Monitoring programs should use surrogate methods to obtain initial dry deposition estimates, because it may be quite a few years before we have a good measurement technique for monitoring dry deposition. (For example, by measuring certain air concentrations, plugging them into models, and estimating a deposition velocity, the dry deposition rate can be estimated).
- Since dry deposition is a significant portion of total deposition, we need to estimate/measure it and be able to apportion man-made from natural contributions by:
  - reviewing available techniques,
  - considering alternatives, and

  - developing and implementing the best available measurement methods.
- Dustfall should be investigated as to its role in buffering acid emissions in the prairies. Current available data on dustfall should be examined for relevancy.

d. Wet Deposition

- Wet deposition data should be collected in Western Canada that is consistent and comparable to other networks, i.e., all should use a standard, recognized method.
- At the minimum, daily event samples should be made at some sites.
- The objectives of wet deposition monitoring should be clearly established, i.e., regional versus site specific.

e. Data Integration

- There exists in Alberta a large array of data being collected and stored in private systems. Most often, the data is not made available to researchers nor is it in a usable format for use as an input to models. Attention should be paid to the various "needs" groups and their data-handling requirements. In particular:
  - "needs" groups should be given access to existing data;
  - available data should be catalogued;
  - there should be database uniformity;
  - improvements in data format and storage for ease in data handling should be undertaken;
  - data retrieval should be made available in an efficient manner; and
  - data records should address the end user's needs.

3. BIOLOGICAL CONCERNS

Facilitators: Don Johnston, Douglas Leahey

Introduction

Participants in this part of the workshop were asked to reach a consensus about the recommendations for future research on the biological issues identified in the morning sessions.

Initial discussions included many issues better covered under headings other than biological. For example, agent identification and quantification to allow loading studies was agreed to be necessary, but it should be a research goal under a different heading, like Monitoring and Modelling. The importance of research in the monitoring and modelling areas was recognized, but it should be dealt with under another heading.

A second issue of equal importance concerned communication. Although not a biological research issue, it was discussed to ensure that the public (particularly directly affected groups like farmers), scientists, industry, and government exchange research ideas and results freely to achieve their common goals. Making science understandable was no greater an issue than having scientists understand the concerns of others.

The above issues were recognized as research needs but were handled at other sessions with different headings from the biological ones addressed in this session. The following recommendations were made for biological research:

Recommendations and Rationale

a. **Researchers should be required to determine the biological effects of acid-forming emissions on various ecosystems, especially:**
   - **the dose:response effect to northern acid-sensitive soils in comparison to other areas of the province;**
   - **the dose:response effect of emissions located in naturally sensitive areas; and**

- **the effect and availability of biological agents when in an acid-emission environment as compared to a non-acid-emission environment.**

The rationale for the above includes:

- a tendency to transpose the results of research from one area to another area of the province in which the conditions are very different;
- dose:response work in natural areas and with sensitive systems/organisms will add to the single agent, single species, and controlled environment research already done to allow a broader understanding of the effects of acid-forming emissions; and
- biological activity and availability may be affected by acidity. Research, for example, into selenium and aluminum, in acid and non-acid environments should add to knowledge about this aspect of the ecosystem.

b. **Research into the health of humans and animals in close proximity to the emission source is recommended. This research should include both acute and chronic effects through:**

- **veterinarian evaluation of animal health, reproduction, feeding, and growth;**
- **development of animal dose:response models; and**
- **epidemiologic studies of exposed human populations.**

Rationale: The reason for studying exposed populations is that detection of effects is most likely in the most exposed group. Although generally long term, these studies, when combined with other research such as the medical diagnostic review, will gradually give the much needed information about what, if any, health effects occur in humans and animals exposed to acid-forming emissions.

c. **Research is required to help establish relative risk; that is, the risk which exists in the acid-emission environment when compared to that in a non-acid-emission environment. This should include:**

- **integration of results from other research concerning loading, dose:response, and acute versus chronic exposure to give a picture of the ecosystem sensitivity and adaptability;**

- comparisons of acid-emission biological effects with the expected biological effects if a process is substituted in an attempt to reduce acid emissions;
- close liaison with communications experts, scientists, industry, the public, and the regulators to ensure that the meaning of relative risk is understood; and
- research and liaison with appropriate groups to ensure that all understand how relative risk is applied to risk management.

Rationale: Those supporting this recommendation wanted some baseline information about health risks to allow them to make wise choices. It was recognized that the ideal risk-free environment doesn't exist but that a better environment can result from selecting the least harmful process when weighing the economic, social, and environmental impacts.

d. Research of high quality must be encouraged to ensure better data. This may be to the detriment of small but inadequate studies of the type which have been too prevalent in the past. This should include:

- integration of research from other studies (deposition, dispersion, monitoring) with health studies; and
- monitoring programs brought into balance with the interpretive abilities of others.

Rationale: It was felt that more co-ordination of research was required to give higher quality data by concentrating the research and avoiding duplication. Also, there is little need to spend monies developing the tools to measure in parts per billion when our interpretive abilities are struggling to develop the tools to measure biological effects in parts per ten thousand.

4. EMISSION CONTROL TECHNOLOGY

Facilitators: Dennis Leask, Phillip Ullman

Discussions revolved around three areas and the following recommendations were put forward:

a. Prevention and Control Systems

- The economic impact of any prevention and/or control system must be documented before implementation. An objective of any control system should be the most emission removal for the least cost, e.g., for sulphur, Rockwell precombusters via flue gas desulphurization.
- It was recommended that emission output data be known and documented for Alberta for any experimental control systems. This output emission must then be compared to the known existing levels and assessed as per the objective.
- More stringent standards that require additional control systems should have adequate lead time/adjustment period for affected industries.

b. Research into Better Emission Control Technology

- The lead time for new technology development is long. It is important that all agencies understand this comment in order that an orderly cost-effective approach to better emission controls can be achieved. The standards cannot be unrealistic with respect to best practical/available technology; therefore, technical research is critical.
- It was recommended that emission-control standards should have an ongoing review process and that this process should provide an opportunity to update these standards.
- The comments under prevention and control systems also apply lead time for adjustment by affected industries.

c. Increased Focus on Abatement and Reducing Emissions

- It was recommended that specific focus be placed on fugitive and transient emissions research where such focus is warranted and justified. Examples for research include flare pits, flare stacks, incineration, and oil and gas facilities fugitive emissions.

SUMMARY AND GENERAL RECOMMENDATIONS

The discussions that took place at the workshop were thought provoking and highly practical in relation to the overall objectives. The recommendations that came out have been documented here for consideration by research managers when directing research efforts.

An issue identified by several groups in the morning issue identification session, but which fell outside the scope of the afternoon sessions, was, "Is there a problem?" Although it is apparent from the recommendations for research that there are many questions yet to be explored, it was not clear if Alberta had an acid deposition problem. Currently, this question is the subject of the multimillion-dollar Acid Deposition Research Program, and it is expected that the answer to this basic question will be brought into clearer focus as ADRP progresses. **It would be helpful to open the discussion at future symposium/workshops by asking a few speakers to summarize what effects have been identified in Alberta due to acid-forming emissions.**

When organizing future workshops such as this, it is suggested by CPANS/APCA that the following comments be given some consideration:

- The interest and involvement of attendees at the workshops would be enhanced if they believed that their input and recommendations would carry some weight with research decision-makers. **Therefore, it is recommended that a mechanism be established by the Steering Committee to track the response by research managers to these recommendations.** In this way, attendees at the next workshop could be informed as to how the previous recommendations were received and used by environmental research decision-makers.
- The response by research managers to recommendations is related to presentation of recommendations in clear terms supported by a well thought out rationale.

Failure of recommendations to be accepted is usually because the recommendations are too general in nature or because they are not well supported. **Therefore, it is recommended that future workshop organizers be given a goal that research recommendations must be stated clearly and must be well supported.**

In making this second recommendation we understand what whenever large groups are involved in discussion that it is easier to reach consensus on general suggestions than on specific recommendations. However, the extra effort needed to reach agreement on specific recommendations is well worth it if it means the recommendation will be accepted by decision-makers.

- Finally, **those involved in the preparation of this report recommend that improvements be considered in the format of note-taking during future workshops.** To capture the essence of the audience discussion, which ultimately provides a rationale for future research needs, use of a tape recorder of someone taking shorthand would be an asset. Flipcharts used in this workshop were principally used as a recording media for key phrases and brief notes. Unfortunately, this approach does not provide any detail for later review.

PART 4: LIST OF PARTICIPANTS

S. Abboud
Alberta Research Council,
Terrain Sciences Department
PO Box 8330, Station F
Edmonton, Alberta T6H 5X2
  tel: (403) 450-5470

P. Abramowicz
Greenpeace
1530 - 10 Ave. S.W.
Calgary, Alberta T3C 0J5
  tel: (403) 228-3159

M. Abugov
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
  tel: (403) 297-3758

P.A. Addison
Canadian Forestry Service
351 St. Joseph Blvd.
Ottawa, Ontario K1A 1G5
  tel: (819) 997-3350

B.C. Alleyne
Pollution Study Group
Environment Council of Alberta
4th Floor, Donsdale Place
10709 Jasper Avenue
Edmonton, Alberta T5J 3N3
  tel: (403) 427-6724

R.P. Angle
Air Quality Control Branch
Alberta Environment
6th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta T5K 2J6
  tel: (403) 427-5893

E.G. Baddaloo
Research Management Division
Alberta Environment
Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
  tel: (403) 427-6254

G.A. Baker
Consultant
1032 Kerfoot Crescent SW
Calgary, Alberta T2V 2M7
  tel: (403) 253-8786

B. Baker
Faculty of Environmental Design
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
  tel: (403) 284-9441

K. Baker
Box 509
Canmore, Alberta
  tel: (403) 673-2449

G. Bako
Public Advisory Committee
Environment Council of Alberta
10533 - 130 Street
Edmonton, Alberta T5N 1X9
  tel: (403) 455-1232

F.D. Barlow
Alberta Research Council
Atmospheric Science Department
700, 4445 Calgary Trail South
Edmonton, Alberta T6H 5R7
  tel: (403) 438-0555, ext. 316

W.N. Barnes
Alberta Forest Service
9945 - 108 Street
Petroleum Plaza North
Edmonton, Alberta T5K 2G6
  tel: (403) 427-3587

R.N. Bazuk
Kelsey Institute of Applied
  Arts and Sciences
P.O. Box 1520
Saskatoon, Saskatchewan S7K 3R5
  tel: (306) 933-6452

R.E. Beaty
Alberta Environment
4th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta T5K 2J6

D. Blackmore
Public Lands Division
Alberta Forest Service
4th Floor Petroleum Plaza
South Tower
9915 - 108 Street
Edmonton, Alberta T5K 2C9
  tel: (403) 427-5209

D.H. Boyd
Western Research
1313 - 44 Avenue NE
Calgary, Alberta T2E 6L5
tel: (403) 291-1313

M. Bradshaw
Petro-Canada Inc.
P.O. Box 369
Cochrane, Alberta
tel: (403) 932-2241

R.N. Briggs
Director, Pollution Control
Alberta Environment
9820 - 106 Street
Edmonton, Alberta
tel: (403) 427-6270

D. Bruchet
Canadian Petroleum Association
1500, 633 - 6 Avenue SW
Calgary, Alberta T2P 2Y5
tel: (403) 269-6721

E.R. Brushett, Manager
Environmental Protection Department
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-8121

T.G. Brydges
Science Advisor
LRTAP Liaison Office
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4
tel: (416) 667-4885

G. Butler
Calgary Health Services
Station C, PO Box 4016
Calgary, Alberta T2T 5T1

K.W. Campbell
Consultant
Sub-Surface Technology
and Instrumentation
227 - Silvercreek Cl. NW
Calgary, Alberta

N. Carlson
City of Wetaskiwin
Wetoka Health Unit
5610 - 40 Avenue
Wetaskiwin, Alberta T9A 3E4

J.W. Case
Case Biomanagement
1865, 500 - 4 Avenue SW
Calgary, Alberta T2P 2V6
tel: (403) 264-9822

J. Century
J.R. Century Petroleum Consultants
200, 640 - 12 Avenue SW
Calgary, Alberta T2R 0H5
tel: (403) 262-2835

D.S. Chadder, Principal
Promet Environmental Group Ltd.
1338P - 36 Avenue NE
Calgary, Alberta T2E 6C3
tel: (403) 250-9123

B. Chapman
McKinnon Allen & Associates
Western Ltd.
1115 - 46 Avenue SE
Calgary, Alberta T2G 2A5
tel: (403) 243-4345

M.H. Chaudhry
Lakeland College
Vermilion Campus
Vermilion, Alberta T0B 4L0
tel: (403) 833-8588

M.J. Chorel
Director of Generation Planning
TransAlta Utilities Corporation
110 - 12 Avenue SW
PO Box 1900
Calgary, Alberta T2P 2M1
tel: (403) 267-7314

D. Colley
Western Research
1313 - 44 Avenue NE
Calgary, Alberta T2E 6L5
tel: (403) 291-1313

K. Corbet
Occupational Medicine
The University of Calgary
3330 Hospital Drive NW
Calgary, Alberta T2N 4N1
tel: (403) 220-7269

M. Cottle
HSA & Community Health
13th Floor Clinical Sciences Bldg.
University of Alberta
Edmonton, Alberta T6G 2G3
tel: (403) 432-6450

A.D. Crerar
Chief Executive Officer
Environment Council of Alberta
8th Floor, Weber Centre
5555 Calgary Trail
Edmonton, Alberta T6H 5P9
tel: (403) 427-4193

B.R. Croft
Dome Petroleum Limited
PO Box 200
Calgary, Alberta T2P 2H8
tel: (403) 231-8081

F. Cullen
Environmental Devices
PO Box 7125, Station "E"
Calgary, Alberta T3C 3L8
tel: (403) 242-6877

D.L. Dabbs
Dabbs Environmental Services
1870, 500 - 4 Avenue SW
Calgary, Alberta T2P 2V6
tel: (403) 265-6021

T.S. Dai
Syncrude Canada Ltd.
10030 - 107 Street
Edmonton, Alberta T5J 3E5
tel: (403) 429-9223

R.M. Danielson
Kananaskis Centre for Env. Research
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5264

M. Davies
Concord Scientific Corporation
#1890, 500 - 4 Avenue SW
Calgary, Alberta T2P 2V6
tel: (403) 264-2140

S. DePaoli
Procor, Sulphur Services
310, 10333 Southport Road S.W.
Calgary, Alberta T2W 3X6

G. DeSorcy, Vice Chairman
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-8261

P. Dickey, Manager
Safety & Environmental Affairs
Shell Canada Limited
PO Box 100, Station M
Calgary, Alberta T2P 2H5
tel: (403) 232-2090

J.D. Dilay
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-8137

D.E. Dimma
Ontario Ministry of the Environment
Air Resources Branch
880 Bay Street, 3rd Floor
Toronto, Ontario
tel: (416) 965-4516

S.G. Djurfors
Syncrude Canada Ltd.
10030 - 107 Street
Edmonton, Alberta T5J 3E5
tel: (403) 429-9286

D. Dougherty
Chemex Labs Alberta (1984) Ltd.
2021 - 41 Avenue NE
Calgary, Alberta T2E 6P2
tel: (403) 291-3077

B. Dryden
Chevron Canada Resources Ltd.
500 - 5 Avenue SW
Calgary, Alberta T2P 0L7
tel: (403) 234-5185

P. Erickson
Environmental Protection Service
Environment Canada
Twin Atria #2, 2nd Floor
4999 - 98 Avenue
Edmonton, Alberta
tel: (403) 468-8028

A.L.P. Ertugrul
Concord Scientific Corp.
2 Tippett Road
Downsview, Ontario M3H 2V2
tel: (416) 630-6331

R.G. Evans
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4

B. Farion
Energy Resources Conservation Board
4920 - 51 Street
Red Deer, Alberta
tel: (403) 340-5454

R. Fenton
Alberta Agriculture
P.O. Bag #1,
Airdrie, Alberta TOM OBO
tel: (403) 948-6868

G. Ferguson
Pollution Study Group
Environment Council of Alberta
26 Lincoln Way SW
Calgary, Alberta T3E 6X3
tel: (304) 249-0390

R.J. Fessenden
Alberta Research Council
Natural Resources Division
Terrain Sciences Department
6th Floor, Terrace Plaza
4445 Calgary Trail South
Edmonton, Alberta T6H 5R7
tel: (403) 438-0555

R. Findlay, Manager
Environmental Affairs
Amoco Canada Petroleum Company Ltd.
Amoco Canada Building
444 - 7th Avenue, SW
Calgary, Alberta T2P OY2
tel: (403) 233-1741

K. Fisher
Monitrex Engineering Ltd.
Bay 7, 2200 - 39 Avenue NE
Calgary, Alberta T2E 6P7
tel: (403) 291-3590

Mary and Murray Forster
Box 488
Crossfield, Alberta TOM OSO
tel: (403) 946-5111

J. Gainer
Consultant
144 Wood Oak Way SW
Calgary, Alberta T2W 3R9
tel: (403) 238-0440

B. Gestermann
Walter Kollo Str. 37
6232 Bad Soden 1
West Germany

G.W. Gibbs, Executive Director
Occupational Health Services
Alberta Workers Health, Safety
and Compensation
10709 Jasper Avenue, 5th Floor
Edmonton, Alberta T5J 3N3
tel: (403) 427-8067

D. Gignac
Botany Department
University of Alberta
Edmonton, Alberta

R. Goldstein
Environmental Assessment Department
Electric Power Research Institute
3412 Hillview Avenue
PO Box 10412
Palo Alto, California 94303
tel: (415) 855-2593

R.B. Gorby
Shell Canada Ltd.
PO Box 100, Station M
Calgary, Alberta T2P 2H5

H. Goss
Laboratory and Pollution Control Supervisor
Canadian Occidental Petroleum Ltd.
General Delivery
Balzac, Alberta TOM OEO
tel: (403) 226-0022, ext. 69

R.G. Gossen
Esso Resources Canada Ltd.
237 - 4 Avenue
Calgary, Alberta
tel: (403) 237-2713

D.N. Graveland
Monenco Consultants Ltd.
Suite 205, 740 - 4 Avenue S
Lethbridge, Alberta T1J ON9
tel: (403) 320-0411

L. Graves
Mobil Oil Canada Ltd.
Box 800
Calgary, Alberta T2P 2J7
tel: (403) 267-4185

M. Hansen
Western Research
1313 - 44th Avenue NE
Calgary, Alberta T3E 6L5
tel: (403) 291-1313

C. Harris
Okanagan College
Box 1668
Salmon Arm, B.C. VOE 2TO
tel: (604) 832-8729

J. Hedenstrom
Chairman, Pollution Study Group
Environment Council of Alberta
Box 2161
Pincher Creek, Alberta TOK 1WO
tel: (403) 627-5173

H.R. Heffler
Tera Environmental Consultants
1115 Kensington Road NW
Calgary, Alberta T2N 3P2
tel: (403) 283-9467

D. Henderson
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4

H.S. Hicklin
H.E.S. Ltd.
408 - 11 Avenue NW
Calgary, Alberta T2M 0B9
tel: (403) 277-0302

L. Holizki
Environment Protection Department
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-3697

N. Holowaychuk
Alberta Research Council
4445 Calgary Trail South
Edmonton, Alberta T6H 5X2
tel: (403) 438-0555

R. Houlihan
Energy Resources Conservation Board
640 - 5th Ave. S.W.
Calgary, Alberta
tel: (403) 297-3510

R.G. Huget
Concord Scientific Corp.
Downsview, Ontario M3H 2Y2

B. Hume
Atmospheric Environment Service
Environment Canada
4999 - 98 Avenue
Edmonton, Alberta T8N 3J1
tel: (403) 420-3143

W.C. Irwin
Pollution Study Group
Environment Council of Alberta
11163 - 36A Avenue
Edmonton, Alberta T6J 0E6

D. Jaeger
Mount Royal College
1324 - 75 Ave. S.W.
Calgary, Alberta
tel: (403) 257-6290

L. James
Pollution Control Division
Renewable Resources, G.N.W.T.
6th Floor, Courthouse Building
Yellowknife, NWT X1A 2L9

K. Jamil
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-8399

D. Jasper
Western Co-operative Fertilizers Ltd.
P.O. Box 2500
Calgary, Alberta T2P 2N1
tel: (403) 279-1224

R. Jensen
Canadian Occidental Petroleum Ltd.
#1500, 635 - 8 Avenue SW
Calgary, Alberta
tel: (403) 234-6700

B. Johnston
BP Resources Canada Limited
333 - 5 Avenue SW
Calgary, Alberta T2P 3B6
tel: (403) 237-1369

D. Johnston
Health Centre
Dome Canada
PO Box 200
Calgary, Alberta T2P 3H8
tel: (403) 231-1051

F. Johnston
The DPA Group Inc.
930, 540 - 5 Ave. S.W.
Calgary, Alberta

H.C. Jones, Chief
Fisheries and Aquatic Ecology Branch
Tennessee Valley Authority
128 SPB
Knoxville, TN 37902
tel: (615) 632-3319

M. Kavanagh
Department of Biology
University of Calgary
2500 University Dr. N.W.
Calgary, Alberta T2N 1N4

G. Kjersem
Shell Canada Ltd.
PO Box 309
Cochrane, Alberta TOL OWO
tel: (403) 932-2201

A. Kosteltz
Environment Canada (Ottawa)
Place Vincent Massey
351 St. Joseph Blvd.
Hull, Quebec K1A 1C8
tel: (819) 994-3064

M. Kostuch, Member
Steering/Organizing Committee
Box 1288
Rocky Mountain House, Alberta TOM 1T0
tel: (403) 845-3668

S.V. Krupa
University of Minnesota
Department of Plant Pathology
495 Borlaug Hall
1991 Buford Circle
St. Paul, Minnesota 55108
tel: (612) 625-7294

S. L'Hirondelle
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 427-4380

D. LaBerge
Chemex Labs Alberta (1984) Ltd.
2021 - 41 Avenue NE
Calgary, Alberta T2E 6P2
tel: (403) 291-3077

E.J. Laishley
University of Calgary
Department Biology
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5283

D.M. Leahey
Western Research
1313 - 44 Avenue NE
Calgary, Alberta T2E 6L5
tel: (403) 291-1313

D.M. Leask
Mount Royal College
4825 Richard Road SW
Calgary, Alberta T3E 6K6
tel: (403) 240-6173

L.J. Lechner
Air Pollution Control
Saskatchewan Environment
3085 Albert Street
Regina, Saskatchewan S4S 0B1
tel: (306) 787-6195

A.H. Legge
Kananaskis Centre for Env. Research
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6084

S. Leggett
Department of Biology
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5948

R. Leininger
Alberta Environmental Centre
Alberta Environment
Bag 4000
Vegreville, Alberta T0B 4L0
tel: (403) 632-6761, ext. 229

G. Leitch
LRA Ltd.
506, 609 - 14 Street NW
Calgary, Alberta
tel: (403) 270-3255

G.L. Lesko
Syncrude Canada Ltd.
Research Department
PO Box 5790, Station L
Edmonton, Alberta T6C 4G3

M.J. Lesky, Head
Environmental Planning
Husky Oil Operations Ltd.
PO Box 6525, Station D
Calgary, Alberta T2P 3G7
tel: (403) 298-6767

Chow-Seng Liu
Alberta Environment
8811 - 43 Avenue
Edmonton, Alberta
tel: (403) 427-5872

J.P. Lodge
Consultant in Atmospheric Chemistry
385 Broadway
Boulder, Colorado 80303
tel: (303) 449-7712

W.S. Macdonald
Pollution Control Division
Alberta Environment
Oxbridge Place
9820 - 106 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-5893

B.L. Magill
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 422-2070

P. Mahaffy
The King's College
Chemistry Department
10766 - 97 Street
Edmonton, Alberta T5H 2M1
tel: (403) 428-0727

J. Marsh
1312 - 39 Street
Edmonton, Alberta T6L 2M7

H.C. Martin
LRTAP Liaison Office
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario M3H 5T4
tel: (416) 667-4803

C.P. Mason
Nova Corporation
32nd Floor, 801 - 7 Avenue SW
Calgary, Alberta T2P 2N6
tel: (403) 290-7342

A. Masuda
Alberta Environment
Oxbridge Place
9820 - 106 Street
Edmonton, Alberta
tel: (403) 427-5828

D. Maynard
Canadian Forestry Service
Northern Forest Research Centre
5320 122 Street
Edmonton, Alberta T6H 3S5

D.A. McCoy
Canterra Energy Ltd.
555 - 4th Avenue SW
PO Box 1051
Calgary, Alberta T2P 2K7

C. McCulloch
Jim Love and Associates
R.R. #2
Didsbury, Alberta TOM OWO
tel: (403) 335-4933

D.A. Mead
Environmental Affairs
Shell Canada Ltd.
PO Box 100, Station M
Calgary, Alberta T2J 2H5
tel: (403) 232-2068

L. Melnychyn
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-3186

G.R. Merrick
Pollution Study Group
Environment Council of Alberta
1203 Stafford Drive
Lethbridge, Alberta T1H 2B9
tel: (403) 328-3088

V. Millard, Chairman
Energy Resources Conservation Board
640 Fifth Avenue SW
Calgary, Alberta T2P 3G4

E. Morin
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4

J. Morse
Greenpeace Foundation
831 - 4 Street N.E.
Calgary, Alberta
tel: (403) 230-7006

R.A. Mutch
Pollution Study Group
Environment Council of Alberta
Medicine Hat College
299 College Drive
Medicine Hat, Alberta T1A 3Y6
tel: (403) 529-3973

M.T. Myres
Department of Biology
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6789

J. Nagendran
Alberta Environment
4th Floor, 9820 - 106 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-5888

R.K. Natsukoshi
Manalta Coal Ltd.
PO Box 2880
Calgary, Alberta T2P 2M7
tel: (403) 294-5491

L.B. Noble
Esso Resources Ltd.
237 - 4 Ave. S.W.
Calgary, Alberta
tel: (403) 237-3614

M. Nosal
Department of Mathematics and Statistics
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4

C. Palmer
Alberta Environment
Earth Sciences Division
3rd Floor, Cousins Building
Lethbridge, Alberta T1J 4B3
tel: (403) 381-5322

P. Papirnik
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 422-2071

D. Parkinson, Director
Kananaskis Centre for Env. Research
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6344

S. Patel
Petro-Canada
150 - 6 Avenue SW
PO Box 2844
Calgary, Alberta T2P 3E3
tel: (403) 296-6064

D.V. Pattison
Pattison Consulting Services
2126 Chilcotin Road NW
Calgary, Alberta T2L 0X1
tel: (403) 282-5441

E. Peake
Kananaskis Centre for Env. Research
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-3194

B. Peel
Alberta Power Limited
10035 - 105 Street
Edmonton, Alberta T5J 2V6
tel: (403) 420-7614

M.L. Phillips
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario M3H 5T4

M. Philpot
Chevron Canada Resources
23 Gillespie Crescent
Red Deer, Alberta
tel: (403) 234-5000

A.R. Pool
Pan Canadian Petroleum Ltd.
PO Box 2850
150 - 9 Avenue SW
Calgary, Alberta T2P 2S5
tel: (403) 290-2083

R. Portelli
Concord Scientific Corporation
2 Tippett Road
Toronto, Ontario
tel: (416) 630-6331

C. Powter
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 427-4380

B.D. Prasad
Head, Mining Section
Oil Sands Department
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-3397

C.L. Primus
Assistant Deputy Minister
Alberta Environment
Environmental Protection Services
14th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-6246

M.G. Prior, Head
Toxicology Group
Alberta Environmental Centre
Alberta Environment
Bag 4000
Vegreville, Alberta T0B 4L0
tel: (403) 632-6761

David Pryce
BP Canada Inc.
333 - 5 Avenue SW
Calgary, Alberta T2P 3B6
tel: (403) 237-1312

M. Psutka
Esso Resources Canada Limited
237 - 4 Avenue SW
Calgary, Alberta T2P 0H6
tel: (403) 237-4873

H. Quan
TransAlta Utilities Corporation
110 - 12 Avenue SW
Box 1900
Calgary, Alberta T2P 2M1
tel: (403) 267-7627

J.B. Railton, Manager
Environmental Planning
TransAlta Utilities Corp.
110 - 12 Avenue SW
Box 1900
Calgary, Alberta T2P 2M1
tel: (403) 267-3637

M. Raizenne
Health and Welfare Canada
HPB Building, Rm. 65-B
Tunney's Pasture
Ottawa, Ontario K1A 0L2
tel: (613) 990-8859

P.S. Ramalingam
Canadian Union College
Box 534
College Heights, Alberta T0C 0Z0
tel: (403) 782-3381, ext. 278

S.S. Rao
Microbiology Laboratories
National Water Research Institute
Canada Centre for Inland Waters
867 Lakeshore Road
PO Box 5050
Burlington, Ontario L7R 4A6
tel: (416) 336-4924

H. Regier
Alberta Environment
3rd floor, Cousins Bldg.
Lethbridge Community College
Lethbridge, Alberta

P. Reid
2027 Bowness Road NW
Calgary, Alberta
tel: (403) 283-7854

E. Reinl-Dwyer
Pedology Consultants
9120 - 37 Avenue
Edmonton, Alberta
tel: (403) 463-7875

W.G. Remmer
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-8174

E.C. Rhodes
Department of Geography
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6065

A. Richards
Leitch Richards Associates
506, 609 - 14 Street NW
Calgary, Alberta
tel: (403) 270-3255

M. Riddle
Monenco Consultants Ltd.
#400, 801 - 6 Avenue SW
Calgary, Alberta T2P 3W3
tel: (403) 298-4579

C. Ro
462 - 78 Avenue NE
Calgary, Alberta
tel: (403) 275-8291

J. Robert
Dome Petroleum Limited
PO Box 200
Calgary, Alberta T2P 2H8
tel: (403) 231-8082

J. Roschlaub
Peace Country Acid Lake
Committee Member
Rural Route No. 1
Debolt, Alberta T0H 1B0

N. Ross
Concord Scientific Corporation
1890, 500 - 4 Avenue SW
Calgary, Alberta T2P 2V6
tel: (403) 264-2140

P.M. Roth
Consultant
21 Catsgill Court
San Anselmo, CA 94960
tel: (415) 456-0333

R.D. Rowe
Dept. of Mechanical Engineering
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-7185

C. Rubec
Lands Directorate
Environment Canada
Ottawa, Ontario K1A 0E7
tel: (819) 953-1447

H.S. Sandhu
Alberta Environment
Research Management Division
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 422-2071

B. Schnitzler
Assistant Manager
Gas Department
Energy Resources Conservation Board
9th Floor, 640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-7322

M. Schroeder
Western Research
1313 - 44 Avenue NE
Calgary, Alberta T3E 6L5
tel: (403) 291-1313

A.R. Schulz
Pollution Control Division
Alberta Environment
Oxbridge Place
9820 - 108 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-5893

B. Schwalm
Alberta Sulphur Research
Department of Chemistry
University of Calgary
2500 University Dr. N.W.
Calgary, Alberta T2N 1N4
tel: (403) 220-3141

T. Sears
Baymag Plant
200, 1144 - 29 Avenue NE
Calgary, Alberta T2E 7P1
tel: (403) 250-3562

W.A. Seddon
Atomic Energy of Canada
Chalk River, Ontario K0J 1J0
tel: (613) 584-3311

M. Semchuck
Senior Technologist
Gas Department
Energy Resources Conservation Board
9th Floor, 640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-4182

J.P. Senyk
Canadian Forestry Service
506 W Burnside Road
Victoria, British Columbia V8Z 1M5
tel: (604) 388-0688

S. Shewchuk
Saskatchewan Research Council
15 Innovation Blvd.
Saskatoon, Saskatchewan S7N 2X8
tel: (306) 933-5437

J.H. Shinn
Lawrence Livermore National Lab.
P.O. Box 5507, L-524
Livermore, California 94550
tel: (415)422-6806

H.P. Sims, Director
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4
tel: (403) 427-3096

G.A. Singleton
Research Management Division
Alberta Environment
14th Floor, Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta T5J 3N4

D. Skappak
Energy Resources Conservation Board
2nd Floor, Provincial Building
4920 - 51 Street
Red Deer, Alberta T4N 6K8
tel: (403) 340-5454

R. Sloan
Mount Royal College
4825 Richard Road SW
Calgary, Alberta T3E 6K6

I.R. Smyth
Executive Director
Canadian Petroleum Association
1500, 633 - Sixth Avenue SW
Calgary, Alberta T2P 2Y5

T. Spackman
Alberta Environment
Air Quality Control Branch
2nd Floor, Deerfoot Square
2938 - 11 Street NE
Calgary, Alberta T2E 7L7
tel: (403) 297-8271

W. Speller
Petro-Canada
150 - 6 Avenue SW
PO Box 2844
Calgary, Alberta T2P 3E3
tel: (403) 296-5331

D. Spencer
Energy Resources Conservation Board
640 - 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: (403) 297-3184

S. Stephansson
Nova Corporation
PO Box 2535
Postal Station M
Calgary, Alberta T2P 2N6
tel: (403) 290-7343

M. Strosher
Kananaskis Centre
University of Calgary
2500 University Drive N.W.
Calgary, Alberta T2N 1N4
tel: (403) 220-6137

P.W. Summers
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4
tel: (416) 667-4796

R. Tamasi
Canadian Occidental Petroleum Ltd.
#1500, 635 - 8 Avenue SW
Calgary, Alberta
tel: (403) 234-6063

S.A. Telang
Kananaskis Centre for Env. Research
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6375

P. Temoin
Husky
Box 6525, Station D
Calgary, Alberta
tel: (403) 298-6770

B. Thompson
Wm. C. Thompson & Associates
122 Varsity Green Bay NW
Calgary, Alberta T3B 3A7
tel: (403) 266-4492

B. Thomson
Atmospheric Environment Service
2nd Floor, Twin Atria Bldg.
4999 - 98 Avenue
Edmonton, Alberta T6B 2X3
tel: (403) 420-3143

W. Thorne
Energy Resources Conservation Board
640 - 5th Ave. S.W.
Calgary, Alberta

E.L. Tollefson
Dept. of Chemical and Petroleum
Engineering
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5754

J.E. Torneby
Pollution Control Division
Alberta Environment
Oxbridge Place
9820 - 108 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-5893

D.O. Trew
Water Quality Control Branch
Pollution Control Division
Alberta Environment
9820 - 106 Street
Edmonton, Alberta T5K 2J6
tel: (403) 427-5828

G.S. Trump
Mount Royal College
4825 Richard Rd. S.W.
Calgary, Alberta T3E 6K6
tel: (403) 240-6167

L.W. Turchenek
Alberta Research Council
Terrain Sciences Department
4445 Calgary Train South
Edmonton, Alberta T6H 5R7
tel: (403) 438-0555

E. Twumasi
Shell Canada Ltd.
PO Box 309
Cochrane, Alberta T0L 0W0
tel: (403) 932-2201

P. Ullman
Environmental Management Associates
1510 - 10 Avenue SW
Calgary, Alberta T3C 0J5
tel: (403) 245-1623

S. Visser
Kananaskis Centre for Env. Research
The University of Calgary
2500 Univesity Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5264

D.H. Vitt
University of Alberta
Department of Botany
Edmonton, Alberta
tel: (403) 432-3380

G. Walker
Agricultural Fieldman
County of Wetaskiwin No. 10
5109 - 51 Street
Wetaskiwin, Alberta T9A 2A5
tel: (403) 352-3321

R. Wallace
Program Manager
Acid Deposition Research Program
Dominion Ecological Consulting Ltd.
#200, 601 - 17 Avenue SW
Calgary, Alberta T2S 0B3
tel: (403) 228-0074

R. Warren
Environmental Design
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6182

R. Webb
R. Webb Environmental Services Ltd.
910 London House
505 - 4 Avenue SW
Calgary, Alberta T2P 0J8
tel: (403) 264-6266

H. Webber
Manager, Gas Department
Energy Resources Conservation Board
9th Floor, 640 5 Avenue SW
Calgary, Alberta T2P 3G4
tel: 297-8506

G. Webster
Dome Petroleum Limited
PO Box 200
Calgary, Alberta T2P 2H8
tel: (403) 231-8079

W.M. White
Box 29
Department of Geography
The University of Calgary
2500 University Drive NW
Calgary, Alberta T2N 1N4
tel: (403) 220-5587

J.H. Wiens
Waste Management Branch
B.C. Ministry of Environment
810 Blanchard Street
Victoria, BC V8Z 2J2

F.A. Williamson
Environmental Planning
TransAlta Utilities Corporation
Box 1900
Calgary, Alberta T1P 2M1
tel: (403) 267-7593

R. Wilson
Waste Management Branch
B.C. Ministry of Environment and Parks
810 Blanchard Street
Victoria, BC V8Z 2J2

L. Wojtiw
Alberta Research Council
4445 Calgary Trail South
Edmonton, Alberta

B.W. Worbets
Canterra Energy Ltd.
P.O. Box 1051
Calgary, Alberta T2P 2K7
tel: (403) 267-9443

D. Wotton
Manitoba Environment
Bldg. 2, 139 Tuxedo Avenue
Winnipeg, Manitoba T3N 0H6
tel: (204) 945-7081

M. Wright
Gulf Canada Resources Inc.
P.O. Box 130
Calgary, Alberta T2P 2H7

I. Zaborski
Energy Resources Conservation Board
Chemical Laboratory
3512 - 33 Street NW
Calgary, Alberta T2L 2A6
tel: (403) 297-2450

J. Zaman
Dept. of Chemical Engineering
The University of Calgary
2500 University of Calgary NW
Calgary, Alberta T2N 1N4
tel: (403) 220-6529

M.J. Zelensky
Consultant
84 Bermondsey Rise NW
Calgary, Alberta T3K 1T9
tel: (403) 274-7901